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THE CLYDE ESTUARY AND FIRTH. AN ASSESSMENT OF PRESENT KNOWLEDGE--ETC(U)
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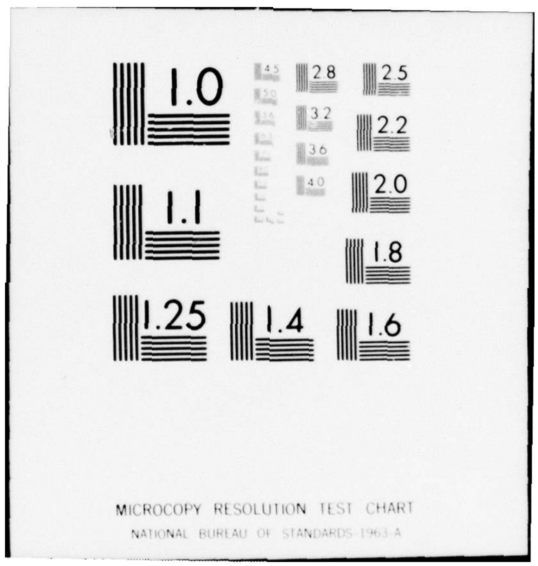
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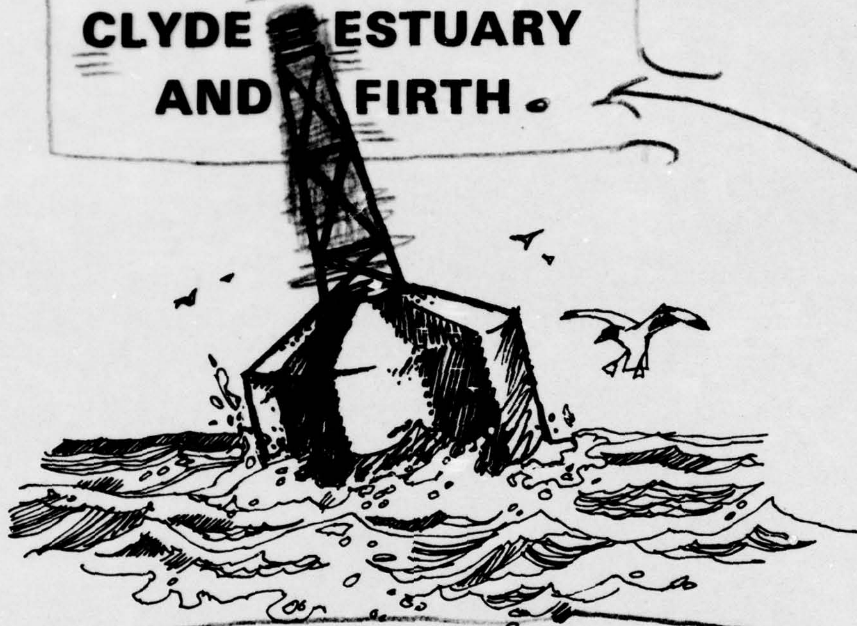
THE CLYDE ESTUARY AND FIRTH.



An Assessment of Present Knowledge.

Compiled by
Members of the Clyde Study Group

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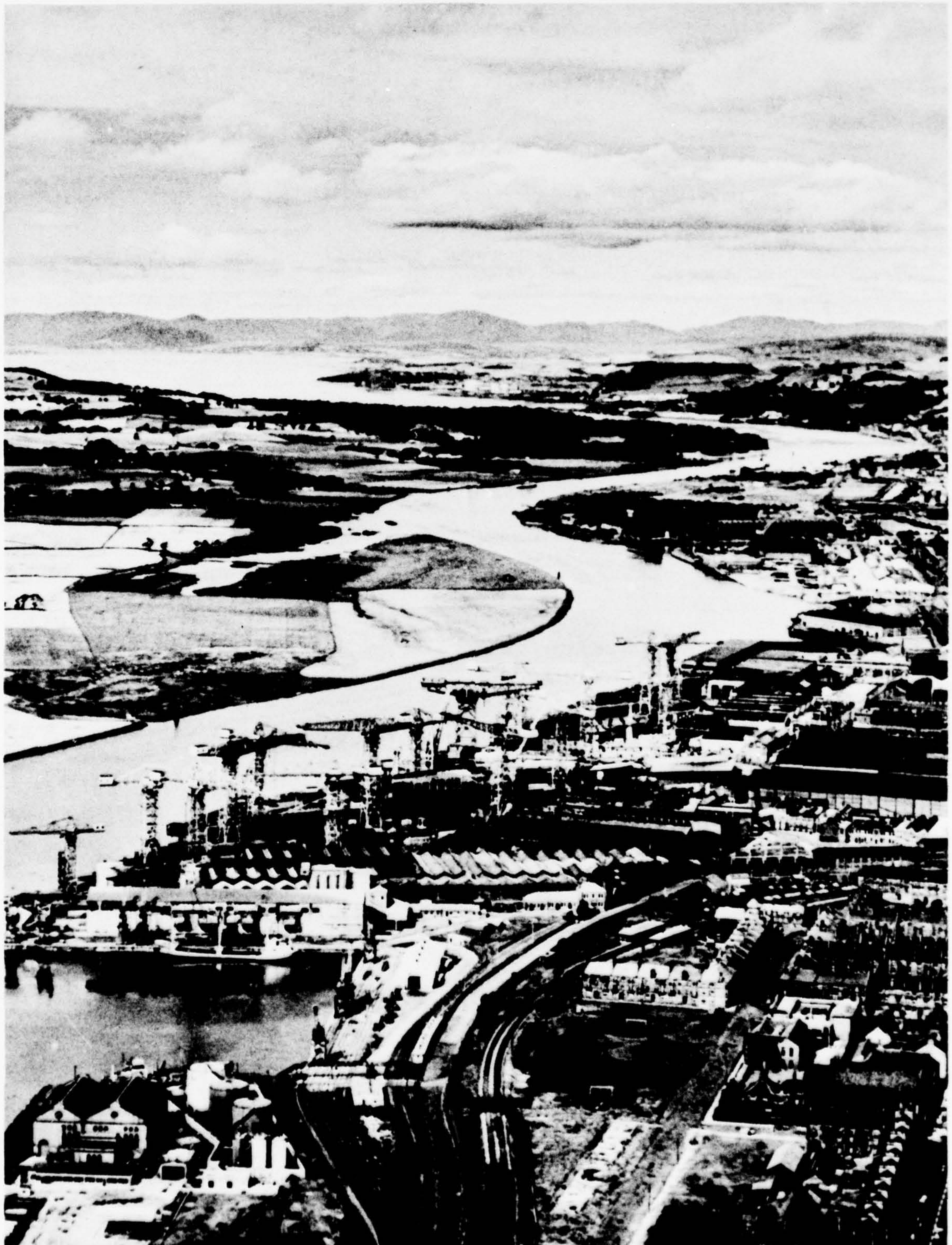


A panoramic view of the Clyde Estuary, from above Clydebank, before the Erskine Bridge was constructed.

PREFACE

In its task of encouraging and executing research in the natural environment, the Natural Environment Research Council has underlined the need for more basic background information about estuarine systems, how they function and how they respond to the uses we make of them.

Over the last twelve to eighteen months, a number of regional groups have formed with specific estuaries as their focus. They usually have representation of Government Departments, River Authorities, Sea Fisheries Committees and research scientists drawn from the universities and regional laboratories. In some instances, these groups were initiated directly by NERC, in others their genesis lay with other agencies. In all cases, however, NERC has encouraged their activities by participating in their meetings, and by seeking Study Group views on the research needed to resolve problems specific to local estuaries. These groups have been persuaded to undertake background appraisals of scientific information available for each estuary. The first such appraisal on 'The Severn Estuary and Bristol Channel', prepared jointly by NERC Institutes, the University of Bristol and University College, Swansea, was published at the end of 1972. This report of the Clyde Study Group is the second of this series, and others are expected to follow. The reports aim to gather information to a single locus, to help identify gaps in knowledge or understanding, and so to stimulate the most appropriate research programmes which will provide a sound scientific base for the wise use of our estuaries.*

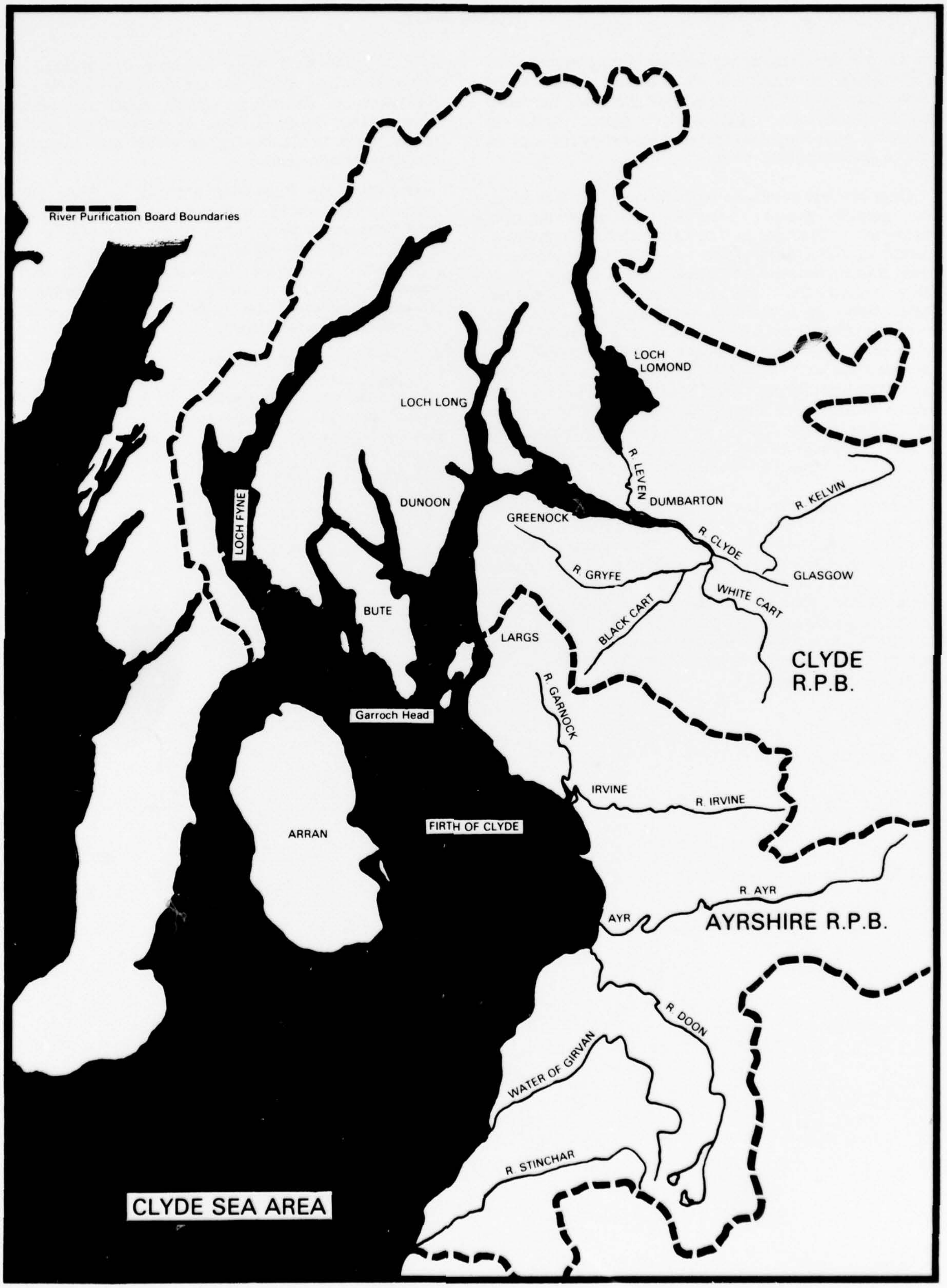
In addition to helping promote the activities of regional groups, NERC has set up a Working Party on Research in Estuaries, which seeks to identify topical and regional gaps in knowledge, and to recommend to Council a coherent and integrated programme of research.

The Working Party has close links, through its membership, with the regional study groups and will take account of their views in its final report. One activity of the Working Party has been to gather together a selective bibliography of estuarine research publications relevant to British interest; this should supplement the regional appraisals, such as this, of individual estuaries.

The Clyde is in the forefront of concern for British estuaries, since it will be a centre for developing industry in the next decades. It happens that we know more about this estuary than many others in Britain, partly from the long history of investigation carried out by the Scottish Marine Biological Association at Millport, and partly through recent scientific investigation by the Scottish Fisheries Department, the Clyde River Purification Board, University scientists, and the Institute of Geological Sciences. Nevertheless, the anticipated development in the Clyde area will make demands on our knowledge of the estuary. It is hoped that this report will serve as a useful starting point for the identification of new programmes designed to fulfil those needs.

January 1974 — *R. J. H. Beverton*
Secretary of Council

**The Severn Estuary and Bristol Channel. An assessment of present knowledge. NERC Series C. No. 9, 1972.*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R. GRYFE
GLASGOW
WHITE CART
BUTE
BLACK CART
LARGS
CLYDE R.P.B.
R. GARNOCK
Garroch Head
IRVINE
R. IRVINE
ARRAN
FIRTH OF CLYDE
R. AYR
AYR
AYRSHIRE R.P.B.
R. DOON
WATER OF GIRVAN
R. STINCHAR
CLYDE SEA AREA

SYNOPSIS

G W Heath, NERC, Institute for Marine Environmental Research, Plymouth

APPRAISAL

The appraisal of knowledge about the Clyde Estuary and Firth has revealed an area about which a great deal is known. This is not surprising, since the Millport Laboratory* of the Scottish Marine Biological Association has operated there for a long time and has been the home of a number of distinguished marine scientists. The physical and other features of the area are described in a number of the papers that follow and several maps.

The long history of industrial development in the upper part of the estuary, which is referred to in a paper by the Clyde River Purification Board, means that it is an area moderated a great deal by man's activities both through receiving effluent and waste as well as by dredging to keep the shipping channels open in the upper reaches of the estuary. Modern developments, of which the Hunterston Power Station is a noteworthy example, are likely to be sited in the lower parts of the estuary and, indeed, there are proposals for development of deep water port facilities in the Hunterston/Fairlie area.

More generally the review reveals the Clyde Estuary, unlike some other estuaries, to be fairly stable in nature with a bottom composed of fine sediments apparently little reworked. Whilst information available is extensive and bodies such as the Clyde River Purification Board comparatively advanced in their understanding of the need to exercise control over both new developments and time honoured customs of effluent disposal, it is noteworthy that little of the information is quantitative in nature. The descriptive assessment has considerable value, and indicates areas where more information may be needed and where future research effort might be most profitably focussed.

GEOLOGY

The Clyde Basin is complex and made up of many sea lochs resulting from the glacial scouring of the Pleistocene age; in places this 'over deepened' the solid rock bed. The sediments of the deep parts of the Basin are of glacial, post glacial and recent origin and do not completely fill these holes. Elsewhere, there are sandy muds and sand, and gravel deposits in the littoral and sub-littoral areas are in some cases being extracted. In deeper waters, manganese nodules have been found, indicating that the rate of sedimentation is comparatively slow, so that dumping of excavated material or sludge may drastically alter the sediment regime. Further information on sediment transport and deposition is needed before predictions about the distribution of effluents and the effects of dumping can be made.

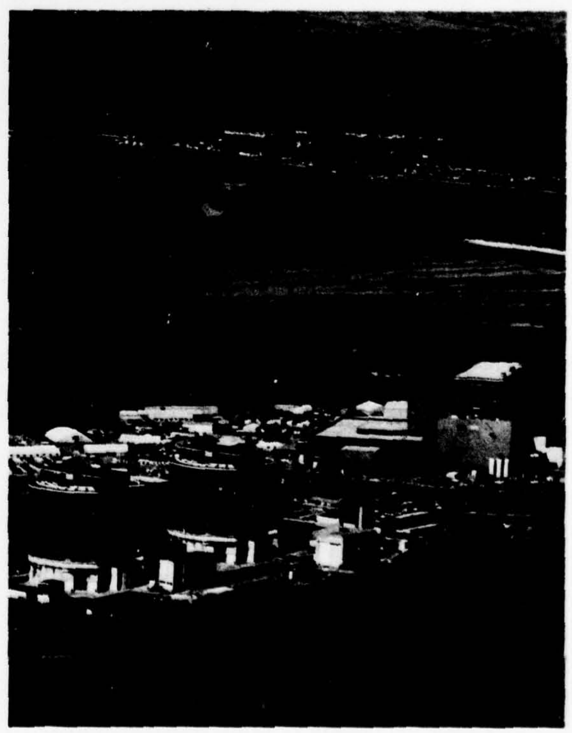
WATER MOVEMENTS

In comparison with other estuaries in the UK, the Clyde has a relatively small tidal range and hence tidal currents are weak. The circulation pattern indicates a partly mixed system and residence time of water in the Firth may be about nine months. All these factors indicate the relatively stable nature of the system and emphasise the need to find out if this stability is likely to be endangered. For instance, the fresh water input to the system is small and as the Clyde River Purification Board paper shows it is sometimes inadequate to carry effluent, so that anaerobic conditions develop. In addition to the River Clyde, three major contributaries discharge into the inner estuary, but in spite of the heavy rainfall over the catchment input is relatively small in relation to the volume of the estuary. The input of fresh water from the area as a whole is considerably moderated by the storage capacity of Loch Lomond. Further moderation of input might therefore cause concern.

CHEMISTRY

Pollution in the Clyde has three main origins. First, domestic sewage and industrial effluent from urban areas carried by the River Clyde and its tributaries; secondly, the dumping of sludge and sewage off Garroch Head; and thirdly, the enrichment of the Irvine Bay area through the discharge of nitrogenous effluents from industrial plant. Hence, the major pollutant is organic materials but heavy metals and other substances will be included. There are in addition the special problems of thermal addition from Power Stations and the release of radioactivity.

An aerial view of Hunterston Power Station. The twin buildings in the foreground are part of Hunterston A complex. The block-shaped building—Hunterston B—is still under construction.



Now operated jointly by the Universities of Glasgow and London.

Sludge dumping has been the subject of considerable survey programmes which have revealed an increase in the levels of Pb, Cu, Cr, Cd, Ag, Sn and Zn in sediments and the benthic fauna. There is some evidence of a change in the character of the benthic community in the areas where sludge is dumped; this is probably a consequence of increased organic matter in the sediment. Its significance in terms of the total productivity of the biomass of the area has not yet been assessed but clearly should be. The more general problems which arise from the increase in heavy metal pollution through sludge dumping and the increase or alteration in algal bloom through nutrient enrichment are however another matter. Knowledge does not yet exist which can tell us how much of such pollution the area can tolerate; nor indeed is it possible to say yet whether or not present pollution of that kind has reached a level where it has measurable environmental effects, however strong suspicion may be.

This review has so far indicated an estuarine system which is physically rather stable, that is biologically rich and hence productive. The activities along its shores and hinterland indeed suggest it is subject to additional man-induced inputs of both productive factors such as nitrogen and heat, and deleterious factors such as heavy metals and organo-chlorines. We need to know much more about the physical environment of the biological variables if we are to model this system sufficiently well to predict consequences of present or future pollution.

BIOLOGY

The general outlines of the seasonal phytoplankton changes have been followed for some years, but detailed quantitative studies are very sparse. The available data on spring 'outbursts' suggests that they follow periods of calm weather when reduced vertical mixing coincides with an increase in light. With few exceptions the spring sequences of *Skeletonema* dominance appear to be regular annual features and though the timing varies greatly from one year to another, quantitative information on the seasonal changes in the subsidiary components of the phytoplankton flora could possibly indicate both short- and long-term environmental changes.

The seaweeds of the area have been well studied for a long time, not only their occurrence and distribution, but also as a possible resource for harvesting. Knowledge of their variety, abundance and distribution might be used to provide evidence of changes but uncertainty as to how complete were the early collections makes comparisons difficult. Nevertheless, attempts are being made to determine which species may have disappeared and to see if such events are indications of any particular environmental changes. There are, of course, differences to be seen between the Firth and the Estuary proper, but these reflect the different salinity range as well as the considerable pollution that exists on the Port Glasgow/Greenock shore, where both the flora and fauna are much restricted. The fauna of the mud flats provides a food supply for a large number of wildfowl and statistics are available on their distribution in relation to food supply.

The Clyde is one of the few estuaries for which there are extensive data on the benthos, although at present only qualitative in nature it could be a basis for future quantitative studies. Studies of benthos made by the SMBA in relation to the effects of Hunterston Power Station remain the only long-term quantitative work and should be invaluable in assessing any future pollution effects in the Hunterston/Fairlie area. These studies refer only to the benthos of the sandy substrate, however and we still lack knowledge about the fauna of muds, where it may be supposed much of the finely divided organic detritus finds its way. Thus it is clear that quantitative studies of the benthos of the fine sediments are needed.

The Clyde fisheries for herring, white fish and shellfish which occur mainly in the outer Firth and North Channel are substantial, with an annual value of about £1.7m of which about half is from the pelagic and demersal fisheries. Fisheries statistics are of course of considerable value in providing an indication of possible changes in the environment. Those for the Clyde show variations which reflect fishing effort as much as variations in the fishable stock. Samples from these fisheries are monitored for residues of heavy metals and organo-chlorines. This work might usefully be supplemented by studying the passage of these materials through the early parts of the food chain upon which the fish depend.

Mud flats in the Clyde Estuary, occurring here on the North and South banks (photo by courtesy of CRPB).

INTRODUCTION

General Information about The Clyde Sea Area

Compiled from information supplied by the Ayrshire and Clyde River Purification Boards.

GEOGRAPHY AND TOPOGRAPHY

The estuary of the River Clyde comprises two distinct parts; an upper, shallow, drowned estuary, and the lower Firth of Clyde, a total area of over 2,500 km^2 contained in a series of deep glaciated basins separated by shallow sills. The Firth itself may be divided into an outer part comprising the area bounded by lines drawn from Farland Head to Skipness Point in the north and from Finnart Point to the Mull of Kintyre in the south; and an inner region of fjords running north into the highlands of Argyll, from Loch Fyne in the west to the Gare Loch in the east. These main features and the areas controlled by the Ayrshire and Clyde River Purification Boards are shown on page iv. Of the total mainland catchment area of 8,265 km^2 more than half (5,415 km^2) is controlled by the Clyde River Purification Board while the remainder (2,850 km^2) is the responsibility of the Ayrshire River Purification Board.

The Clyde basin (2,600 km^2) is the biggest single catchment, draining the Renfrewshire hills, the plateaus of south and east Lanarkshire and the Campsie Fells. The Loch Lomond catchment (785 km^2) drains a mountain area rising to 800-1000m in the north and the Campsie Fells and Fintry Hills in the east. The whole of the Loch Lomond catchment drains via the R. Leven to the estuary. The remainder of the Clyde River Purification Board catchment (some 2,000 km^2) comprises a very large number of small mountain streams draining the highlands of Argyll to the various sea lochs. The Ayrshire River Purification Board catchment of 2,850 km^2 is drained by short fast-flowing well aerated rivers.

POPULATION

The population of the whole catchment is estimated at 2,535,000, of which more than a million discharge their wastes, and associated trade wastes, to tidal waters. During the summer these figures are increased by the tourist trade, particularly in Ayrshire where there exists overnight accommodation of 29,000 in the coastal resorts. Day trippers are estimated at an average of 160,000 per day along the Ayrshire coast, and towns such as Cardross, Helensburgh, Gourock and Rothesay also receive a considerable influx during the summer.

The major part of the population is contained within the central Clydeside conurbation (1,728,000) while a further 150,000 are clustered along the estuary in the towns of Dumbarton, Helensburgh, Port Glasgow, Greenock, Gourock and Dunoon.

It is estimated that the population of the area will increase by about 10% over the next 25-30 years although in designated overspill areas the increase will be much greater than this. It is possible that the population discharging to the Irvine/Ardrossan Bay area may reach 373,000 by the year 2000, a figure greater than the present population of the whole of Ayrshire.

POLLUTION

Domestic sewage—The upper estuary receives an average input of 0.41 x $10^6 m^3$/day of treated sewage and 0.59 x $10^6 m^3$/day of untreated and partially treated sewage. The latter is discharged to the tidal waters. These flows may be compared with a daily input of 22.3 x $10^6 m^3$ of fresh water, of which 9.2 x $10^6 m^3$ is discharged via the Clyde, Cart, Kelvin and Leven. The lower estuary receives untreated and partially treated sewage from a population of 150,000 estimated at 0.045 x $10^6 m^3$/day. During periods of low flow in the summer the estuary can become totally deoxygenated for a distance of over 20 km downstream of the tidal weir in Glasgow.

In an effort to increase the oxygen content of the estuary various sewage treatment works in Glasgow have been or are being re-constructed. Reconstruction of the Dalmarnock works has brought about an 11% improvement in oxygen levels since 1969. Improvements to the Paisley and Shieldhall works should lead to a substantial reduction in the polluting load by 1976.

The Dalmarnock Sewage Works (photo by courtesy of Glasgow Corporation).

Sewage discharges to the Firth of Clyde are concentrated along the Ayrshire coast. The Largs channel between the mainland and Great Cumbrae receives about 2,400 m^3/day of virtually crude sewage and about 1,900 m^3/day are discharged from communities south of the Heads of Ayr. The remaining communities between Farland Head and the Heads of Ayr give rise to discharges totalling approximately 54,500 m^3/day, with approximately 70% rough screened, 16% settled and the remainder comminuted or crude. It is hoped that future developments in sewage discharge and treatment will ensure that inshore waters and beaches are free of pollution. Where short sewers are in use primary settlement will be required but it is hoped that in general, comminution in conjunction with a long outfall will be used. Hydrographic surveys are being

carried out to ensure that these long outfalls will be sited at points where tidal movement and dilution result in satisfactory dispersion.

Trade effluents—Discharges to both the upper estuary and the Ayrshire coast via local authority sewers include plating, fell-mongery, tannery, slaughterhouse, chemical-industry, oil-refinery, carpet-manufacture, engineering, textile and food-industry wastes.

Among industries which discharge directly to the upper estuary are large power stations, a grain distillery, a pigment manufacturer, textile manufacturers, a paper mill and a metal-plating firm.

Direct discharges of cooling water, chemicals (particularly mineral acids) and certain organic intermediates from nylon salt manufacture are made to the Ardrossan/Irvine Bay. Distillery wastes and food manufacturing wastes are discharged near Girvan.

With the decline of the traditional heavy industries along the Clyde it is envisaged that in the future a greater proportion of modern light industries concentrated on industrial estates will result. If the present trend of chemical engineering is continued a larger proportion of organic intermediates and mineral acids will have to be treated. In many cases small treatment plants at the factories may be necessary to reduce the toxicity of the wastes before they are passed to the local authority sewage works.

Dumping—Deep water, south of Garroch Head, is used by Glasgow Corporation for the disposal of one million tonnes per year of sludge from sewage and industry.

Some 300,000 tonnes of sediment is dredged annually from the Clyde navigation channel and dumped near the mouth of Loch Long. Dredgings from various harbours along the Ayrshire coast, which include some organic matter from local industries, are dumped in the outer Firth.

The practice of dumping wastes is likely to continue until the shortage of raw materials makes their recovery economically feasible or until there is evidence that the economic benefit is outweighed by damage to the environment.

Oil—During the last ten years the tonnage of oil handled annually in the Clyde rose from 3 to 9 million tonnes, and this is still increasing by 10% per annum. In 1971, 56 incidents of oil pollution were reported in the inner Firth and the estuary. Oil is not a very significant pollutant of the outer Firth, but the possibility of a major incident caused either by a tanker passing through or an incident at the Ardrossan oil refinery or at oil depots along the coast, cannot be ruled out.

The new electricity generating station at Inverkip will have its own oil terminal at Wemyss Bay which will handle an estimated 4 million tonnes of heavy fuel oil a year. It is also possible that an oil refinery and terminal will be established in Ayrshire; this might well be followed by an associated petrochemical industry. Such an oil terminal and refinery would give rise to a discharge of up to 5000 m^3/day initially, containing some oil, ammonia, sulphur and suspended solids.

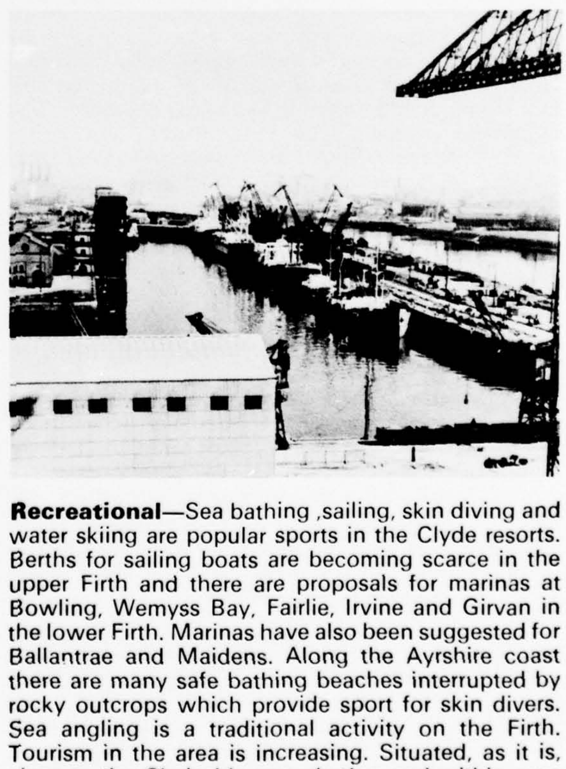
INDUSTRIAL AND RECREATION USES OF TIDAL WATERS

Industrial—Power stations in the upper estuary use 2.6 x $10^6 m^3$/day of cooling water which, at low river flows, can produce a significant temperature rise. Hunterston A power station in the Firth uses 1.9 x $10^6 m^3$/day causing a rise of 1.5 °C between the inlet and outfall. Future developments in electricity generation include the oil-fired station at Inverkip and the Hunterston B nuclear station. The Inverkip station will require 5.8 x $10^6 m^3$/day and Hunterston B 2.4 x $10^6 m^3$/ day of cooling water.

Other industrial uses have smaller cooling water requirements, but the use of saline waters for the buffering of acid wastes is increasing.

As the Firth is the main shipping route into western Scotland and is used for ship trials by the Royal Navy the tonnage passing through it will be likely to increase in the future. Future industrial and port developments along the Firth and estuary will give rise to an increasing number of large container and bulk-carrier ships. The total tonnage handled in 1970 was 16 million tonnes, of which oil accounted for 9 million iron ore 2.8 million and grain 800,000 tonnes.

The River Clyde, looking east towards Glasgow. Rothesay Dock is in the foreground.



Recreational—Sea bathing ,sailing, skin diving and water skiing are popular sports in the Clyde resorts. Berths for sailing boats are becoming scarce in the upper Firth and there are proposals for marinas at Bowling, Wemyss Bay, Fairlie, Irvine and Girvan in the lower Firth. Marinas have also been suggested for Ballantrae and Maidens. Along the Ayrshire coast there are many safe bathing beaches interrupted by rocky outcrops which provide sport for skin divers. Sea angling is a traditional activity on the Firth. Tourism in the area is increasing. Situated, as it is, close to the Clydeside conurbation and within easy reach of northern England, the Firth of Clyde is one of Scotland's most important tourist areas. The income from tourism in Ayrshire was estimated at £12 million in 1964. Increases in the standard of living and the completion of the primary motorway network will undoubtedly lead to a larger influx of visitors.

FISHERIES

Pelagic fish—There has been a decline in the traditional Clyde herring fishery in recent years but in 1970 it still represented 13% of the total Scottish catch and was worth £0.5 million.

The Atlantic salmon is of considerable importance in the outer Firth, where commercial fisheries are sustained off the Girvan, Doon and Ayr river mouths in particular. Regular migrations take place up the River Leven into Loch Lomond but severe pollution has prevented the fish ascending the Clyde for many years. It is hoped, however, that improvements to the sewage works discharging to the Clyde will result in the passage of salmon before 1976.

Demersal Fish—Experiments by the White Fish Authority at Hunterston nuclear power station and at Ardtoe in Argyll have demonstrated the possibility of rearing plaice and sole to marketable size in captivity. The use of part of Hunterston sands for a deep water terminal, would however, make such a development in that area, which is otherwise favourable, less likely.

Shellfish—Shellfish have increased in importance in the last decade, the Clyde catch in 1970 being worth just over £1 million which is 18% of the Scottish total. The principal species are *Nephrops* and scallops but lobsters, winkles and squid are also fished.

SCIENTIFIC AND EDUCATIONAL USES

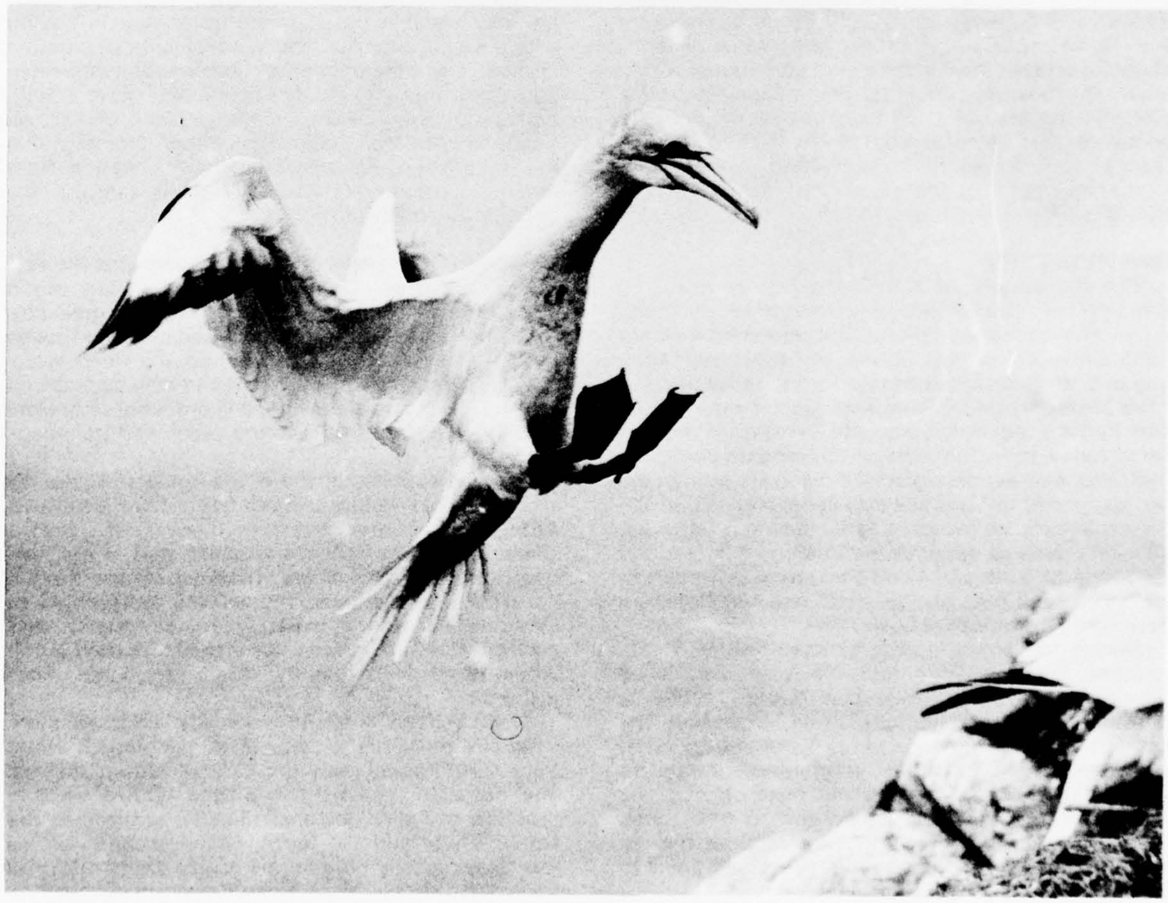
Increasing interest in the environment should ensure that increasing use of the estuary is made by schools, universities and scientific societies.

The research station at Millport has carried out marine research in the Clyde area for 75 years. Although no longer the headquarters of the Scottish Marine Biological Association its use as a centre for undergraduate training will ensure that ecological studies within the immediate vicinity continue. The University of Strathclyde has a research station at Garelochhead, where the main research emphasis at present is on the effects of toxic substances on marine organisms.

Glasgow Corporation arrange annual cruises in the estuary for several hundred senior pupils accompanied by specialist lecturers.

Along the Ayrshire coast there are five sites of special scientific interest covering botanical, geological and ornithological subjects. Ailsa Craig, and Horse Island, off Ardrossan, are noted for bird life.

A gannet (Sula bassana) coming in to land on Ailsa Craig (photo by courtesy of Niall Rankin/Eric Hosking).



GEOLOGICAL INVESTIGATIONS IN THE FIRTH OF CLYDE MADE BY THE INSTITUTE OF GEOLOGICAL SCIENCES

C E Deegan, IGS Continental Shelf Unit II, West Granton Road, Edinburgh EH5 1JA

INTRODUCTION

The first systematic geological mapping of the Clyde Sea area was started by IGS in 1969 when the Institute was asked to produce reconnaissance geological maps of the UK Continental Shelf. The area studied encompasses the Firth of Clyde and sea lochs upstream from latitude 55° 15', that is upstream from a line joining the Mull of Kintyre to the Ayrshire coast at Girvan. Initial work involved geophysical traversing on a 3 km grid using continuous profiling equipment (sparker) and a magnetometer. This was followed by shallow sediment sampling and finally in 1970/71 by diamond drilling. Short supporting cruises for special aspects have also been made, including some work with the submersible Pisces (Eden *et al.*, 1971).

The depth of water and thickness of superficial sediments pose problems for solid rock sampling and so results will be published in two reports; that dealing with superficial deposits is in press, and another on solid geology is in preparation.

The report on the superficial deposits (Deegan *et al.* in press) has maps of bathymetry, rockhead contours, isopachytes of superficial deposits and surface sediment distribution, and includes an appraisal of the facies distribution of the surface sediments. Gravel grade sediments were studied in detail with a view to locating possible commercial deposits. Conclusions are based on examination of grab and sediment core samples from about 900 stations. A map of surface sediment distribution in the Upper Clyde (upstream of the Cumbraes) has been produced by Bowes and Smith (1969).

BATHYMETRY

The bathymetry of the Clyde Sea is mainly a function of glacial scouring during Pleistocene times. Overdeepened hollows cut into solid rock are common in Kilbrannan Sound, off north-east Arran and in Loch Fyne and other sea lochs. These hollows have been only partly filled with glacial, post-glacial and Recent sediments, and still remain as depressions, followed for the most part by modern channels. Indications of selective glacial erosion are seen in the overdeepened troughs of Loch Fyne, and also in the discrepancies in water depth between adjacent channels such as occur at the junction between the East Kyle of Bute and Loch Striven, near Tarbert in Loch Fyne and between the north end of Kilbrannan Sound and the mouth of Loch Fyne.

Glacial movement seems to have followed preexisting fluvial valleys and ice was channelled between established highland areas, such as northern Arran and Kintyre, thus increasing the amount of scour at the ice base. At the south end of Killbrannan Sound from south-west Arran to Campbeltown is a marked rock bar, shown by shallow soundings. This is thought to have been formed when glacial erosion decreased as the ice moved south out of the confining highland areas to the flatter region south of Arran.

SURFACE SEDIMENTS

The distribution of surface sediments is largely controlled by bathymetry (see illustration right). Analysis of samples has permitted the recognition of three major sedimentary facies.

The Coarse Littoral Facies—This includes clean sands and all sediments with a gravel fraction. In the illustration it comprises divisions S, sand; (g)S, slightly gravelly sand; gS, gravelly sand; sG, sandy gravel; (g)mS, slightly gravelly muddy sand; gmS, gravelly muddy sand; and msG, muddy sandy gravel. Sediment thickness rarely exceeds a few tens of centimetres and in most samples 80% of the material is coarser than 62.5 μm (i.e. sand or gravel).

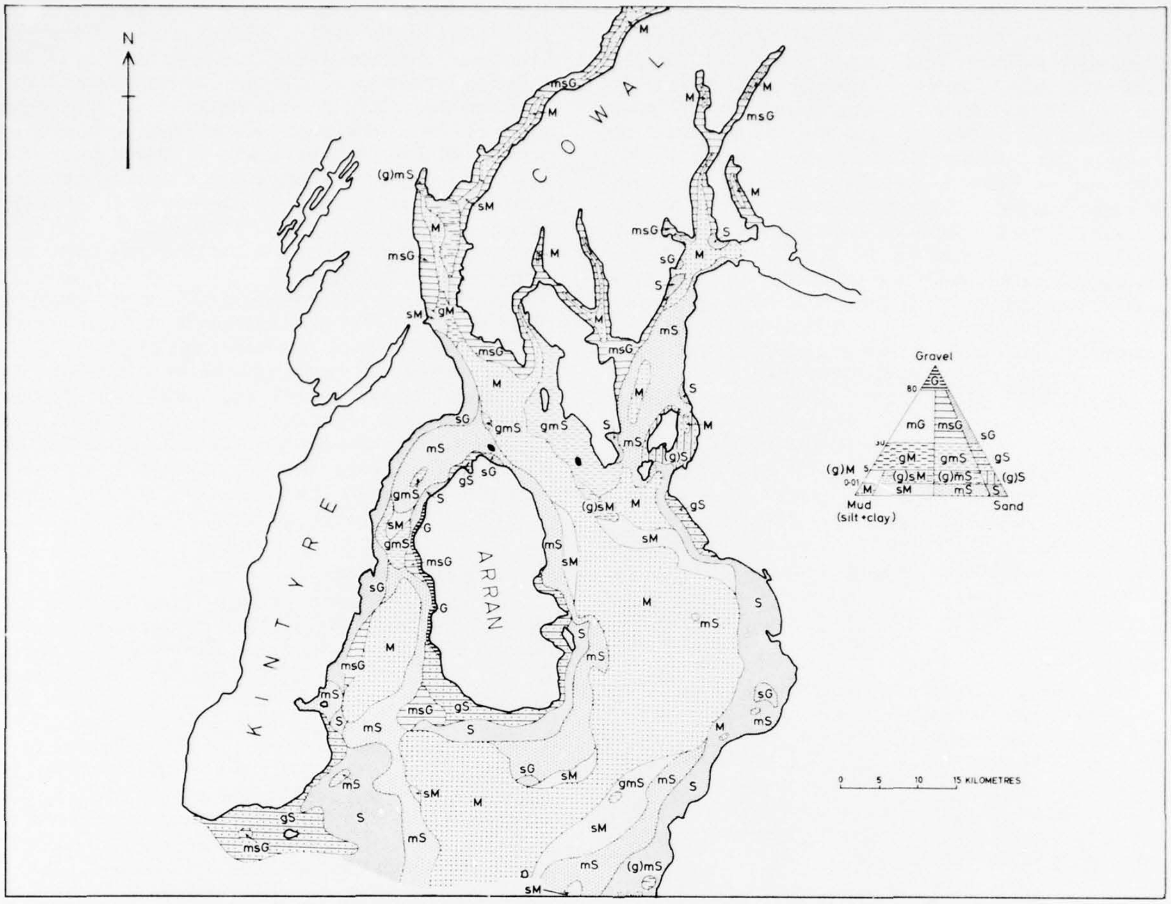
The facies extends from high water to a variable depth, generally less than 40 m. Because deep water occurs close inshore over much of the area and the tidal range is small, the beaches and littoral facies are generally narrow. Off the Ayrshire coast and to the south of Arran and Kintyre gently shelving platforms are found at shallow depth; here the facies is extensive.

The grain size and mineralogy of these sediments are very variable but they are consistent in having a high proportion of coarse material. Lateral variation is great and heterogeneous beach sediments often pass seawards into sandy and muddy gravels, with high proportions of shell material. Sand and gravel fractions of the sediments show considerable mineralogical variations indicating derivation from several sources. Consequently most samples are bimodal and many are polymodal.

The Transitional Facies—This comprises the sM, sandy mud; and mS, muddy sand, divisions of the illustration. Despite having a wide range in grain size the facies distribution is limited because the Coarse Littoral Facies rapidly merges into the deep water Silty Clay Facies. In places the facies may be replaced by a rock cliff and elsewhere it is probably so narrow that the sampling grid spacing precluded its recognition.

A broad expanse of the facies borders the south-west coast of Ayrshire and extends seawards towards Ailsa Craig where a zone of mud separates it from a similar extension from the southern end of the Kintyre Peninsula. The facies continues up the Kintyre coast to Campbeltown and is well represented in Kilbrannan Sound. It is particularly attenuated, and may be absent in places, for instance around Arran where there is frequently very deep water close inshore.

These sediments are lithologically varied but more generally resemble sediments of the deeper water Silty Clay Facies than the Coarse Littoral Facies. The dominant sediment is a mud with a variable proportion of sand and shell material admixed. In the Upper Clyde and sea lochs, mixed samples within this facies locally contain a small quantity of gravel on isolated shoals; such occurrences are too small to



Surface sediment distribution in the Firth of Clyde.

appear in the illustration and in fact some of the gravel grade material appearing in the analyses has certainly come from ships and human activity. The only true gravel grade material in this facies comprises occasional manganese nodules and shell debris. The macrofauna in this facies is much more restricted than in the Coarse Littoral Facies where there are large numbers of species and individuals.

The Silty Clay Facies — This comprises the M, mud, division of the illustration and is the most extensive and lithologically constant facies of the region. It occurs in all the deeper water areas of the Firth and sea lochs. Typically it occurs in a broad belt, up to 13 km wide, from south-west Arran around the east side of Arran through Bute Sound and into Loch Fyne, where water depths up to 220m, occur. It also occurs in Kilbrannan Sound and in the central deeps of the sea lochs. The typical lithology of this facies is only occasionally interrupted by the occurrence of gravels associated with marked submarine outcrops. The only other gravel grade material in this facies consists of manganese nodules.

Sediments are uniformly very fine grained, brown to grey muds with only a very narrow marginal zone within which the coarse fraction increases before passing into the Transitional Facies. Over most of the area the sand fraction does not exceed 1%, consisting mainly of echinoid spines and plates, Foraminifera, ostracods and very fine grained quartz.

An extensive area of apparently coarse grade sand occupies the sea bed in an area east of Arran. This sediment has been reworked to form a faecal pellet sand which also infills burrows; the pellets and burrows may result from the activity of maldanid worms. The facies is characterised by a very prolific microfauna and a restricted macrofauna. A coarsening within the facies west of Ailsa Craig is probably related to a considerable shoaling from around 80 to 50 m to form a barrier plateau which effectively limits the Clyde basin to the south.

RATE OF DEPOSITION AND ORIGIN OF THE SEDIMENTS

Deposition from currents and waves by lateral sedimentation is probably slow in the Clyde except in the estuarine region from the Cumbraes northwards (Allen, 1967). That sedimentation is slow even here is suggested by the abundance of manganese nodules found north of the Cumbraes. Slow deposition is occurring in the deep low energy troughs of the region where flocculated clay and other fine classic material is deposited by vertical sedimentation and is unlikely to be reworked.

Very little information concerning sedimentation rates in this region is available. Moore (1931) measured sedimentation rates within the water column at various intervals and discovered a seasonal variation related to the diatom bloom, the material deposited being diatoms and the faecal pellets of *Calanus finmarchicus* (Muller) which feeds on the diatoms. A delicate banding observed in core samples was attributed to the seasonal diatom bloom. Samples from a locality in Loch Striven, showed a sedimentation rate of ca. 40 cm/100 years. Sedimentation rates in wave affected regions may sometimes be greater, but re-erosion probably maintains a degree of equilibrium. Undoubtedly the effects of dumping and human activity in the upper estuary markedly affect deposition rates.

Gair (1967) showed that dredging operations prevented sediment which enters the head of the estuary from passing downstream into the lower estuary and the Firth, so that little if any, sediment is supplied from the Clyde catchment. There is little evidence of extensive supply of sediment from open marine areas, and the relatively stable area of Silty Clay and Transitional Facies sediments south of Arran shows little sign of movement. Gair (1967) proved that sediment was not moving into the estuary under the influence of the intruding salt wedge.

The main source of new sedimentary material in The Firth must therefore be from rivers entering the sea lochs and those coming from Arran and Ayrshire. Most of these drain either areas of boulder clay, outwash deposits, or raised beach sediments as on the Ayrshire coast. The erosion of such deposits would easily provide the range of grain size and shape and mineralogical variation found.

COMMERCIAL SAND AND GRAVEL PROSPECTS

Examination of gravel grade material indicates that no extensive, well shaped, low shrinkage deposits occur. Well shaped gravels occur in Prestwick Bay and south of Arran but all have a high shrinkage potential. Gravels with low shrinkage potential occur on beaches in areas adjacent to hard Highland rocks e.g. Upper Killbrannan Sound, Loch Fyne and Loch Goil, but they are often of poorly shaped pebbles and remote from potential markets.

Sand and gravel are being extracted from beach workings at Inverkip as part of a scheme to deepen the area for a new marina. At most, gravel is 30 per cent of the deposit and its shape characteristics are poor although shrinkage values are low. Offshore a suction dredger is extracting sand. Clearly the prospects of locating extensive commercial deposits are poor (Eden, 1970) and the exploitation of marginal deposits, for example off south Arran and Prestwick Bay, would require advanced dredging vessels capable of working in exposed conditions.

SUB-SURFACE SEDIMENTS

Superficial sediment thickness is greatest in the deep water areas of the Clyde where it occurs as infilling of glacially scoured hollows. During late and post-glacial times Scotland was subjected to both a eustatic rise of sea level and a more local isostatic upwarping of the land following retreat of the ice. Quaternary succession in different parts of Soctland depends on the local relations between rate of sea level rise and rate of isostatic recovery. Thus in some areas of the Clyde, water depth was sufficient to permit continuous sedimentation throughout the late and post-glacial periods. Areas situated near the level of O.D. however, suffered from periodic transgression and regression resulting in chronologically discontinuous sequences of relatively coarse grained sediments.

Offshore boreholes drilled by IGS 13 km south of Arran show boulder clay overlain by a sequence of late and post-glacial silty clays up to 46 m thick which passes up imperceptibly into the modern Silty Clay Facies surface sediment. In shallower waters towards Ayrshire however, these clays become interbedded with sands and gravels and in such areas as Irvine Bay the superficial sediment sequence is relatively thin and coarse grained. Borehole details are given in Deegan *et al.* (in press).

GEOCHEMISTRY

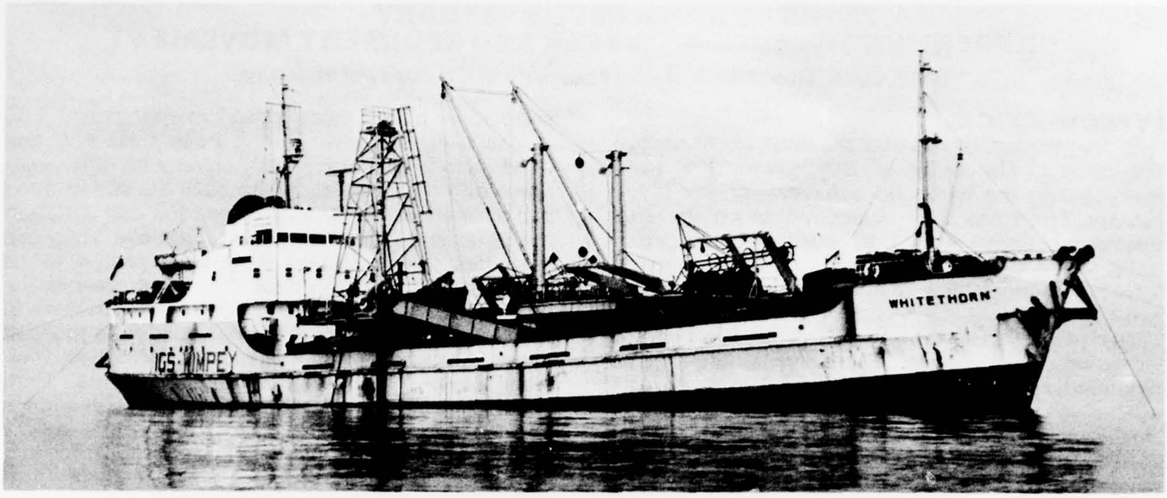
Geochemical investigations by IGS have not yet been extensive. Analyses of manganese nodules and mineral shell debris have been made by both IGS and Calvert and Price (1970). Discrete manganese nodules usually occur in the Silty Clay Facies but mineralised shell debris occurs in shallow water arenaceous sediments. Some interesting results have emerged, and abnormally high concentrations of related minor elements such as lead and zinc occur. A number of sediment samples have been collected for IGS Geochemical Division for a limited geochemical study. A representative suite of samples from a number of areas has also been supplied to the Applied Geochemistry Research Group at Imperial College, London.

SOLID GEOLOGY

An appraisal of the solid geology has been made by IGS but the publication of a comprehensive map and account is awaiting the completion of drilling early in 1972 (Deegan, in prep.).

The dominant structural feature of the region, the Highland Boundary Fault, divides the resistant Dalradian metamorphic rocks of Cowal, north Bute, north Arran and Kintyre from younger formations. Land outcrops can be traced locally offshore for some distance, but the most important geological structures of the marine area are undoubtedly three distinct sedimentary basins first located by gravity measurements made by McLean *et al.* (1970).

Two sedimentary basins occur in the south part of the firth both of which have been investigated by IGS through offshore boreholes. One, to the southwest of Arran, contains a thick sequence of Triassic sediments with gypsum beds, and another, along the coast of south Ayrshire, has yielded red, crossbedded sandstones similar to the Permian exposures at Mauchline in Ayrshire. These basins are separated by a region of high gravity and magnetic anomalies extending from Ailsa Craig to Kildonan in south Arran. Between north-east Arran and the north



The drilling ship M. V. Whitethorn, on location.

Ayrshire coast another sedimentary basin exists, but because of the depth of water it has not yet been possible to identify the infilling strata.

The disposition of geological formations is in part determined by large faults. Two trends of faulting are apparent; one group of north-east/south-west faults clearly extends seawards from Ayrshire and delimits such features as the extension of the Ayrshire coalfield. The other group of north-west/south-east faults, such as the Ardrossan Harbour Fault, have a marked effect on the trend of certain outcrops. Detailed structural studies based on gravity, magnetic and deep seismic work have been made by Hall (1970).

IGS publications dealing with the adjacent land geology include MacGregor and MacGregor (1936), Tyrrel (1928) and Davies (1972); a re-examination of the geology of North Ayrshire (Geological Survey 1 in Sheet 21) has recently been commenced. A fairly comprehensive analysis of the solid geology should be available late in 1972.

CONCLUSIONS

Apart from the inner estuary little is known about rates of sediment deposition and sediment transport paths. Study of these aspects, linked with geochemical investigations would appear to be essential, especially in connection with effluent distribution.

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THE RIVER CLYDE ESTUARY
CURRENT KNOWLEDGE OF WATER AND SEDIMENT MOVEMENT

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INTRODUCTION

During the last eight years, the department of Civil Engineering, University of Strathclyde, has been investigating the hydraulic behaviour of the Clyde estuary. Effort has been concentrated on the area upstream of Gourock, so as to establish the pattern of tides, water circulation, and sedimentation, and to forecast changes that might result from development.

The investigation had two parts. First was a survey using research vessels. Secondly, a large scale hydraulic model of the area was constructed and the effects of various schemes examined. A second, smaller, scale model of a novel type is now under construction, while work on the larger model terminated at the end of 1971. Interest in industrial development is now in areas further seaward and it is hoped that the smaller model will eventually embrace these sites.

DESCRIPTION OF THE INNER ESTUARY

A dredged channel 36 km in length extends from Glasgow to Princes Pier, Greenock. Progressive deepening has taken place since the beginning of the nineteenth century, the minimum depth over most of the length being at present 8.14 m below LWOST. From Glasgow Bridge to 14.5 km downstream, the estuary is now effectively canalised. Thereafter the channel is bounded by tidal mud-flats, the overall width increasing with distance downstream. At Glasgow Bridge the maintained channel ends, while a short distance upstream there is a weir across the river above which a level is maintained approximating to high water neaps.

As well as the River Clyde, three major tributaries discharge fresh water to the inner estuary. The River Kelvin enters 3.2 km below Glasgow Bridge, the Carts at 10.4 km and the Leven at 22.2 km. As can be seen from the inflow characteristics tabulated below, the Leven provides the major fresh water source during dry weather and normal flow conditions. The vast storage of Loch Lomond considerably moderates peak flows from this part of the catchment.

TIDES

The tides in the Clyde estuary result from a co-oscillation with the amphidromic system centred to the west of the Mull of Kintyre.

In comparison with other estuaries in the United Kingdom, tidal ranges are relatively small. The admiralty tide tables quote mean ranges at the entrance to the dredged channel, as 3.08 m springs and 1.89 m neaps, rising to 4.11 m springs and 2.40 m neaps at Glasgow. During neap tides ebb and flood periods are substantially equal with little variation along the channel. At Gourock the spring flood becomes substantially longer than the ebb although the difference is less marked at Glasgow. Thus ebb velocities during springs may be expected to be greater than flood velocities. In contrast, despite the greater prevailing range, a much smaller increase in flood velocities occurs at springs relative to those at neaps. A lag in the time of occurrence of high and low water exists over the length of the channel. High water differs by an average of 39 minutes at springs and 26 minutes at neaps, and low water by 73 minutes and 50 minutes respectively.

In order to provide information for calibration of the hydraulic model, Thomson (1969) undertook a one month survey of tide levels in the maintained channel during the early part of 1966. Temporary gauges were installed at Dalmuir (12.9 km)** and Bowling (16.9 km) to supplement those already existing at Broomielaw (0.4 km), Govan (3.6 km), Rothesay Dock (10.5 km), Greenock (31.3 km) and Gourock (ca. 39 km). A non-harmonic analysis of the results was made by correlating characteristics at adjacent stations. Satisfactory results were obtained for flood and ebb range, high and low water level, and flood and ebb period. Departures in level from high water at $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$ and $\frac{3}{4}$ of the flood period, and $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, of the ebb period, were also examined to provide information on the variation in tide shape. This gave a comprehensive picture of the variation in tide levels throughout the dredged channel during both springs and neaps.

The tides in the inner estuary depart from a smooth curve during the floods of spring tides. This 'hump' becomes magnified with distance upstream and has become more pronounced as the estuary has been deepened. It is a consequence of reflection and resonance of the sixth diurnal tidal constituent, whose period is similar to the natural frequency of the estuary. In his earlier studies for a Clyde hydraulic model, Thom (1949) illustrated by harmonic analysis of tides at Gourock, Bowling and Glasgow, the predominant effect of the third harmonic in producing the hump. Thomson (1969), performed a species analysis as described by Rossiter and Lennon (1965) of spring tide profiles at Gourock and Broomielaw. At the upstream end, a three-fold increase relative to that downstream was found in the sixth diurnal species, supporting the conclusions of Thom. However, Thomson was also able to establish the reason

River	Dry Weather Flow* (95% exceedence)	Normal Flow* (50% exceedence)	Flood Flow* (5% exceedence)
Clyde	7.98 cumecs	22.96 cumecs	140.00 cumecs
Kelvin	1.40 cumecs	5.04 cumecs	26.32 cumecs
Carts	2.66 cumecs	8.54 cumecs	28.00 cumecs
Leven	14.56 cumecs	37.32 cumecs	91.00 cumecs

 Data provided by the Clyde River Purification Board 1966. ** *Distances from Glasgow Bridge.*

for the lack of a corresponding 'hump" on the ebb. During the flood tide the fourth and sixth species are in sympathy, while on the ebb they are in opposition, thus cancelling any tendency for the sixth species to generate a hump at that time. In addition, it was found that the much smoother curves during neap tides resulted from a phase shift in the fourth species.

The hydraulic model showed that a deepened channel led to two humps occurring on the flood, followed by a third on the ebb during spring tides. A mathematical model of tide levels developed by Dr J. Ellis of the Civil Engineering Department, showed that a reaction of the tide generating mechanism to the first surge was responsible for these effects.

CIRCULATION OF WATER

Classification—The inner Clyde estuary falls in the category of a partly-mixed system as described by Pritchard (1955), but application of Simmons' (1955), criterion for normal fresh water flow and average tide range gives a value of 0.042, indicative of well-mixed conditions. These differences in classification can be partly attributed to channel deepening, but some definitions allow considerable departure from the 'ideal' well-mixed condition of no vertical change in salinity with depth (Ippen, 1966). A value of 0.01 has been calculated for the estuary number (Harleman, 1966), but it appears that values of this number in excess of 0.15 indicate well-mixed conditions. Some of the field and model results have been plotted on a diagram of the type proposed by Hansen and Rattray (1966) for classification of rectangular estuaries. The majority fall within the type 2b category, that is partly mixed with appreciable stratification, and indicate approximate equality of effective salt transport through advection and diffusion.

All the above results indicate that lack of knowledge limits precision in the prediction of estuarine circulation patterns.

Field Survey—A field survey programme was started in 1964 and continued until 1968. Data were collected during longitudinal centre-line traverses of the dredged channel over slack water and while at anchor at a single station over a tidal cycle.

SEDIMENTS

Sediment Inflow—Fleming (1970) made a survey of sediment inflow from the River Clyde and the major tributaries of the estuary. River discharges and concentrations of material were monitored at gauging stations on the Clyde, White Cart, Kelvin, and Leven. A total sediment inflow of just under 250,000 tons per annum was estimated, 46% of this entered in suspension via the Clyde, (bed load negligible) 5% in the Kelvin (10% bed load) 24% in the Carts (10% bed load) and $12\frac{1}{2}$% in the Leven (10% bed load). The relatively low inflow of sediment from the Leven results from its short passage from the settling basin of Loch Lomond. Thus $87\frac{1}{2}$% of the annual inflow of sediment is riverborne, $6\frac{1}{4}$% was estimated to result from spillage within the dredged channel and $6\frac{1}{4}$% from solids discharged at sewage works.

As part of this study Fleming applied the Stanford Watershed Model to the Clyde catchment, and encouraging preliminary results were obtained. Derivation of a successful model from this work would enable forecasting of sediment discharge and stream hydrographs to be made at any point.

Deposition and maintenance dredging—Gair (1967) made a historical analysis of sediment removal from the estuary by dredging, using the records of the Clyde Navigation Trust and the Clyde Port Authority. There was difficulty in separating capital and maintenance dredging, and also in making proper allowance for the saturated nature of the material transported; averages for periods of six years and over showed considerable fluctuations. Contributing factors could include varying availability of dredging plant, infrequent maintenance of large downstream areas of low accumulation rate and discontinuance of dredging in some places. However, the general trend seems to be that there is an increase in the maintenance commitment with deepening of the estuary. It was noticeable that this increase occurred solely as a consequence of the additional dredging required upstream of 10 km from Glasgow Bridge, the commitment downstream remaining substantially constant since the channel averaged 5.5 m in depth in 1885.

A rate of removal of 318,000 tons a year was estimated for the period of Fleming's survey, that is an excess of some 75,000 tons a year over the rate of inflow. Gair (1967) proved by both sediment sampling and radioactive tracers that this excess was not supplied from the deep water to seaward by the intruding salt wedge. However, it can be concluded that the estuary is now incapable of passing downstream and out of the system, the sediment entering at the head of the estuary.

Examination by Gair (1967) of successive Admiralty fair charts showed a significant rate of build-up of material in the shallow water between Helensburgh and Ardmore. The average accumulation rate was 100,000 m^3 a year over a 53 year period, most occurring at about the 3 fathom line (5.5 m).

Properties of the bottom sediments—Fleming (1969, 1970) reported that bed material was of fine silt of slowly increasing particle size in the channel between Glasgow and 13 km downstream. At 19 km, fine sand is found and particle size slowly increases with distance downstream.

Gair (1967) examined surface samples taken at the intersections of a half-mile (0.8 km) grid within the area bounded by a line joining Wemyss Bay and Innellan, and the entrance to the River Leven. This includes the Holy Loch, Loch Long and the Gareloch. Mean particle size, standard deviation, skewness, kurtosis, natural unit weight, void ratio, and surface shear strength were measured. Suspended solids settling and consolidation rates, viscosity and shear strength, and the rate of increase of concentration of suspended particles following increase in velocity of water overflowing a bed of the material were also determined.

In the traverses of the dredged channel, measurements of salinity and temperature at two mile intervals and for five foot intervals of depth were

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PHYSICAL CHARACTERISTICS AND TIDES OF THE CLYDE SEA AREA

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The physical characteristics of the Clyde Sea Area have been the subject of research since the nineteenth century, Macadam (1855) and Mill (1885). The latter summarised the position thus:

"The Firth of Clyde is a complicated estuary. It is cut up into many long lochs running up into mountain valleys, and exposed to the rainfall of a moist region, while the river Clyde is relatively small. The water must obviously be largely affected by direct rainfall, which veils the freshening influence of the main river, to which a typical estuary owes its character. The published observations upon the Firth of Clyde, Macadam (1855), and those which I have made, are insufficient to base any generalisation upon; but the interesting nature of the problems presented by the Clyde invites further research'"

Despite the passage of 86 years, Mill's last sentence still holds. Further work by Murray (1886, 1887, 1888, 1891) and by Mill (1892, 1894) from the Scottish Marine Station at Millport helped to further the knowledge of water temperatures. Some of Murray's stations in the Clyde were worked by Marshall and Orr (1927) during the years 1924-26 when a study was made of the relation of the plankton to some of the chemical and physical factors in the Clyde sea area.

However, little measurement of salinities was made until the Department of Agriculture and Fisheries for Scotland (DAFS) started a series of temperature and salinity surveys in the North Channel and the entrance to the Firth of Clyde; (Craig, 1954, 1956, 1959; Craig and Slinn 1957). More recently, Dooley and Steele (1969) measured wind driven currents near the coast in the outer Firth of Clyde.

The upper reaches of the Firth of Clyde were not included in these studies but have been investigated by the Oceanography Section of Strathclyde University. This research stemmed from the construction of a large scale tidal model of the Firth of Clyde for the Clyde Port Authority. Little of the resultant data has been published except Allen (1967) and Ellis (1970) and references in two theses by Gair (1967) and Thomson (1969). Gair's work includes a very detailed analysis of the rheological properties and movement of sediment in the Clyde estuary.

Concurrent with the Strathclyde observations, the Clyde River Purification Board started a programme of sampling for dissolved oxygen (Mackay, 1969; Mackay and Fleming, 1969). This work is reported in greater detail in the Clyde River Purification Board contribution.

At present the Strathclyde results are being analysed and the circulation of estuarine and fiordic sea lochs is being studied in a similar manner to that described in a paper on the hydrography of west coast sea lochs (Milne, 1972). It is hoped that by studying the tidal range, topography, sea bed contours, sill length and width, it will be possible to classify sea lochs in a similar manner to that used for classifying estuaries.

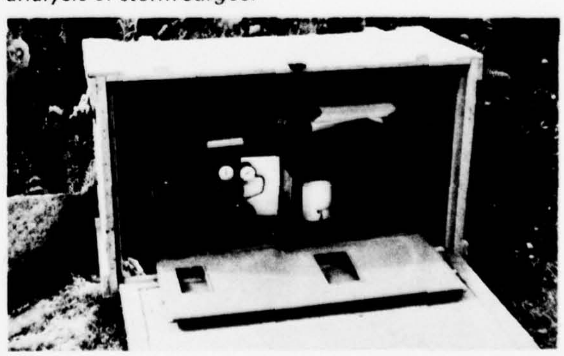
Tidal predictions for the Clyde sea area are based on a harmonic analysis of tide records for one year, from Princes Pier at Greenock. This pier no longer exists, but there is a permanent tide recording gauge at Gourock Pier; for general purposes the Greenock predictions can be used for Gourock. When Strathclyde University was asked to advise the Clyde Port Authority on tide levels in the Clyde Sea Area for the large scale tidal model being built, it was found that insufficient tidal data had been published; so a complete field survey of the region was made. Details of the six permanent float tide gauges and the ten stations occupied with temporary pressure gauges are given by Thomson (1969).

There is little change in tide range or time lag in the area of the firth and sea lochs, because the water is relatively deep. Variations only occur where a topographical feature such as a sill or narrows affects the tidal flow.

Over the last two centuries some isolated observations have been made in the river and estuary. The earliest reference is Bald (1840) who measured the tidal wave in the estuary of the River Clyde. This was followed by work by Deas (1873) and Thomson (1891) on the general tidal characteristics of the river and estuary. The construction of a small tidal model of the Clyde estuary at Glasgow University by Thom (1949) has also assisted in studying the tidal phenomena, and general information is of course given in the Irish Sea pocket tidal stream atlas (Hydrographer of the Navy, 1962).

Recent research on tide levels in the Firth of Clyde has been done in an investigation to study storm tides generated by storm surges. This research (Milne 1971a, 1971b) has shown that the storm tide is amplified as the surge progresses up the firth. At present, records of all the tide levels in the Firth of Clyde are monitored by Strathclyde University, who also use several other permanent tide gauges from Malin Head to Lerwick in a study of storm surges on the west coast of Scotland. From this research it is hoped to be able to predict devastating surges, such as the one which occurred in 1968 on the west coast of Scotland.

A Negretti and Zambra bubble-style portable tide gauge, used for tidal height recordings during the analysis of storm surges.



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SOME OBSERVATIONS ON THE HYDROGRAPHY, CHEMISTRY AND PLANKTON OF THE FIRTH OF CLYDE IN RELATION TO NITRATE-RICH EFFLUENTS

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INTRODUCTION

Pollution in the Firth of Clyde originates from three main centres: the River Clyde and adjoining freshwaters sustaining various degrees of sewage and industrial pollution (Annual Reports of the Clyde River Purification Board); the dumping of sewage and industrial sludge off Garroch Head, south of Bute (Mackay and Topping, 1970; Mackay *et al.*, 1972) and the discharge into Irvine Bay of nitrate-rich effluents from nylon and explosives manufacture, smaller industries in Irvine and the domestic and industrial wastes from an inland population of 175,000. In this report only the results of a broad survey of the Firth of Clyde in relation to nitrate-enrichment, are presented. Detailed studies of Irvine Bay and the dumping ground, covering aspects of pollution additional to nitrate-enrichment, have not yet been completed.

METHODS

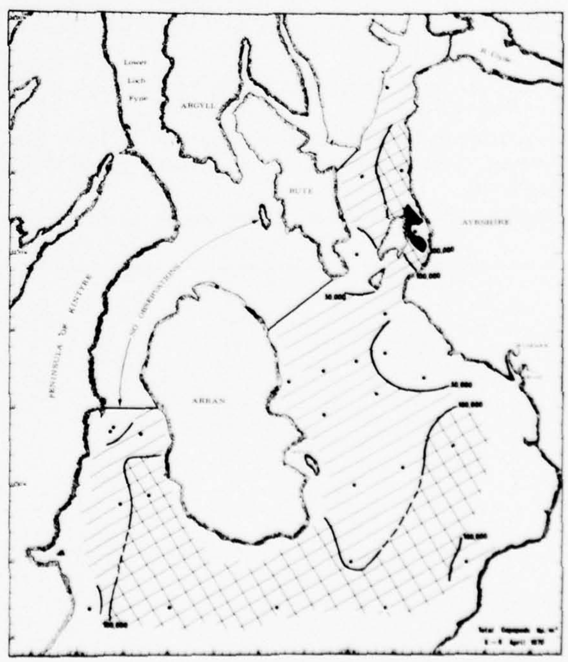
Ship's Position—The ship's position was determined at 15-minute intervals for the general survey of the Firth of Clyde, and every five minutes for Irvine Bay. Ship's speed was held at about 6 knots and 3 knots respectively. Position fixes were obtained by the 'Decca' Navigator System using enlarged charts drawn by the ship's captain for detailed areas. Positions were checked against visual bearings on prominent shore features and on marker buoys.

Temperature and Salinity—In addition to a number of hydrographic sections worked across the Firth, continuous records of temperature and salinity were obtained for a large part of the Firth of Clyde during a 30 hour period on 7-8 April 1970, using the 'Hytech' model 6600T thermo-salinograph, the probes of which were immersed in a stream of sea water drawn by pump from 3 m depth. The records were annotated at 15-minute intervals for the general survey and at every 5 minutes in Irvine Bay to enable the readings to be related to the ship's position. The temperature error was assessed by spot checks using an accurate thermometer; the salinity probe was calibrated by comparison with bottle samples whose salinity was measured by means of a precision induction salinometer.

Water Movement—In order to fully understand the dispersal of nitrate-rich (and other) effluents in Irvine Bay, a thorough understanding of the wind-induced motion over the entire area of the Firth must be achieved. Hence in addition to obtaining 10 days of current measurements using a Plessey recording current meter at a position one nautical mile off-shore in Irvine Bay, parachute drogues (Volkmann *et al.*, 1956) were tracked at various distances offshore, chiefly during 31 March to 3 April, for periods up to 26 hours, their positions being determined at about hourly intervals by means of Decca. The current meter was moored 10 m above the sea-bed in 18 m of water and recorded on magnetic tape the current speed and direction every 10 minutes.

Nitrate—Nitrate (or more accurately nitrate plus nitrite) was determined by a reduction method with copperised-cadmium (Armstrong *et al.*, 1967) using a Technicon AutoAnalyzer. The same pumped sea-water supply was used and the record was annotated in the same way for temperature and salinity. The flow-through time for the nitrate analysis train was 4 minutes 40 seconds plus a further 30 seconds which elapsed in passage from the ship's hull to the equipment. At 6 knots cruising speed, this meant that the ship had covered some ½ mile (0.9 km) during the interval between the entry of the sample and the appearance of its analysis record. On a few occasions very high nitrate values were encountered which put the recorder off-scale but it was usually impractical to manoeuvre the ship to secure further water samples for accurate analysis. Detailed surveys in Irvine Bay were therefore made at 3 knots. All readings have been adjusted for delays in relation to the instantaneous position records.

Plankton—Timed oblique hauls from near bottom were made throughout the area at 6 knots using a Gulf III sampler (Bridger, 1958) equipped with a T.S.K. flowmeter (Nakai, 1954). The station positions are indicated in the map below. Catches were preserved in formalin and were later analysed as follows: the total number of copepods and their percentage composition, other small invertebrates and their percentage composition, larger invertebrates by species (e.g. *Sagitta elegans, Thysanoessa raschii*), eggs of invertebrates, fish eggs and larvae by species as far as possible.



**The sampling station chart above shows the distribution of copepods; charts of other species are available, details on request to the authors.*

RESULTS AND DISCUSSION

Physical Properties—Because of its width and depth, the Firth of Clyde is not a typical estuary, and in many respects can be regarded as a shallow sea. Temperature and salinity usually vary only very gradually and consequently currents due to density gradients may be expected to be very small except perhaps locally near river mouths at times of heavy rainfall. Based on these considerations, Craig (1959) showed that replacement of the water of the Firth must take about nine months. Tidal currents are also very small except near the North Channel and in the narrower, shallower stretches in the north.

Dooley and Steel (1969) showed that the near-shore coastal waters over Ballantrae Bank (off the Ayrshire coast at approximately 55°06′ to 55°07′N) responded very rapidly to changes in the wind, with water movement at all times being parallel to the coast and with speeds of about 1.6% of the long-shore component of the wind velocity. Offshore, however, they found that water movement was more complex and that the flow was part of the large scale wind-induced circulation of the Firth.

During the April 1970 survey, temperature and salinity, as expected, showed only very small variations. Temperature at 3 m only ranged from 5.95°C in the central Firth of Clyde to 6.30°C off south-east Bute. (At this time of year the areas influenced by rivers tended to show higher temperatures than the open sea areas.) Salinity at 3 m ranged from about 31.5‰ at the mouth of the River Clyde to 33.74‰ near the Mull of Kintyre. Much of the Firth of Clyde had salinities in the range 33.2-33.5‰. Vertical temperature and salinity profiles on a number of hydrographic sections between Arran and the mainland revealed small gradients, if any, in the upper 30 m though the water below 50 m was about 0.15°C warmer and slightly more saline at about 33.70‰ than the upper water.

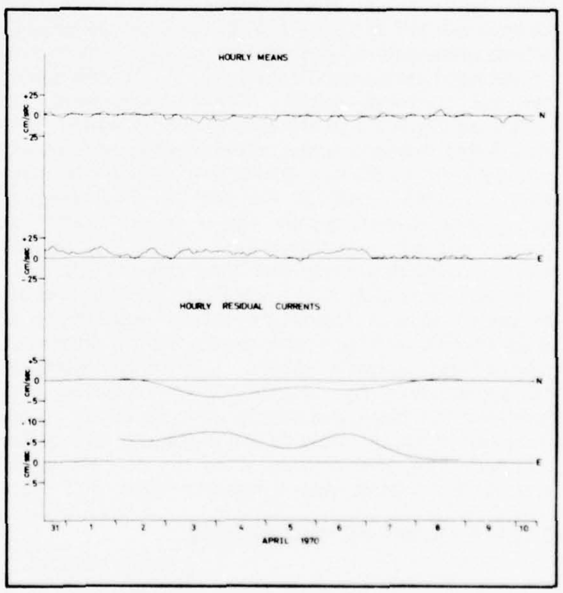
The somewhat higher salinity water near the Mull of Kintyre is attributed to water of the North Channel, while in the upper Firth, lowered salinity is directly attributable to the influence of the River Clyde and to a lesser extent other freshwater sources. A slight decrease in salinity along the Ayrshire coast is associated with the influence of a number of small rivers.

The current measurements made during April 1970 in Irvine Bay agreed qualitatively with the findings of Dooley and Steele (1969). Figure 1 shows a time series plot of the north and east components of the hourly mean currents, and of the hourly residual currents obtained by employing a numerical low pass filter (Godin, 1967). It is obvious from these curves that tidal currents were indeed very small and that any transport that occurred was a consequence of the residual current flow. This flow was towards the south-east, parallel to the shoreline almost all the time, and appeared to be closely related to the local wind which blew persistently from a direction between NW and N for about a week before and during the survey. The situation was more complicated, however, until 6 April the current was closely related to fluctuations in the wind blowing from the north-west, approximately parallel to the shoreline. After 6 April the wind veered towards the north, which resulted in a greatly reduced fetch to the current meter position. Consequently the wind induced drift should have been greatly reduced. This was in fact found for the period subsequent to 7 April, but on the 6th a south-easterly flow exceeding 0.1 m/s was present. This drift was greater than that observed whilst the wind blew parallel to the shoreline, and obviously other factors were involved in its generation. The most probable explanation is that this flow was a result of the increased flow of the rivers Irvine and Garnock which was caused by heavy rainfall on 5 April, setting up secondary circulations in the Bay.

As already indicated, it is only the nearshore zones which are affected directly by the wind. the most notable feature of the complex offshore circulation was the apparent entrainment of the offshore waters inshore. This entrainment will assure greater flushing of the Irvine Bay waters at such times (but will also tend to bring offshore planktonic organisms within the more direct influence of coastal effluent discharges). Otherwise the shallow waters of Irvine Bay provide only limited water for dilution and, because of the coastal boundary, diffusion is limited to an arc of less than 180°.

The results obtained so far give a limited picture of the circulatory mechanism in the Firth and many more measurements will be required, including those made under different wind conditions.

Fig. 1: Series plot of hourly mean currents.



Nitrate

The lowest nitrate values (5–9 μg-at. NO_3–N/l.) occurred inshore along the eastern coastline of Kintyre. A very large area was covered by nitrate in the range 9–11 μg-at/l though here too, the western half of the outer Firth tended to be below 10 μg-at/l and the eastern half 10–11 μg-at/l. Other important features were the markedly higher nitrates on the

western side (12–14 μg-at/l) compared to the eastern side (10.5–12 μg-at/l) of the upper Clyde estuary, and the local areas of high nitrate associated with the nylon factory effluent and with freshening from the rivers Irvine and Garnock. The degree of nitrate enrichment close inshore and the extent of the area encountered, depended mainly on tidal conditions. Seven detailed surveys of Irvine Bay were made in April 1970 but sampling was possible only as far as the 10 fm (18 m) line. Nitrate in excess of 20 μg-at/l. was encountered on six of the seven surveys; three surveys showed areas of above 30 μg-at/l.

Some months later samples from the rivers Irvine and Garnock and from Irvine Harbour were found to contain 400, 210 and 330 μg-at. NO_3-N/l respectively; confirming the suspected high levels from these sources.

An attempt has been made to assess the areas being exposed to high nitrate (Table 1). The mean area has been determined for nitrate above the 12-unit contour as drawn by linear interpolation. For the nylon effluent the mean area was 1.22 km^2 having a mean nitrate content of 22 μg-at. NO_3-N/l. Possibly one-third of this area would have a mean nitrate above 30 units. Based on the evidence of only three surveys of the Irvine-Garnock area made during ebb conditions, the mean area affected was 3.84 km^2 with a mean nitrate concentration of 28 units; no high nitrate was found on three surveys during late flood and high water.

These results relate to dispersal as observed for 3 m depth in late winter under NNW winds. One station worked in 10 fm (18 m) showed rather high nitrate distribution throughout the upper 10 m but an enrichment between 10 and 18 m. Neighbouring stations showed minor nitrate irregularities at scattered depths. The effluent is warmer and slightly less dense than sea water when it emerges from the diffusers. As a result it would tend to rise but there was no visible 'boil' at the surface. The shore is sandy and shelves gently and it seems likely that diluted effluent would have been carried inshore and alongshore with the tidal and wind-driven currents.

In tank experiments at Loch Ewe (Trevallion *et al.*, in prep.) it was found that daily enrichment at 3 μg-at. NO_3-N/l. generally enhanced the growth of plants and animals while daily enrichment at 10 μg-at. NO_3-N/l. considerably increased and modified the plant and animal growth. At 30 μg-at. NO_3-N/l. a major upset to the plant and animal life resulted. The enrichments were devised so as to ensure that nitrate was a limiting factor and were arranged so that 10% volume of water was exchanged for clean sea water daily. In the open sea the water exchange would be much greater and one would not anticipate any build-up of a soluble nutrient like nitrate. Unlike the tank experiments, nitrate enrichment in Irvine Bay might cause other nutrients to become limiting, thus restricting the growth enhancement otherwise expected. Nevertheless, some degree of stress due to nitrate enrichment seems likely within limited areas, but under the variable conditions of dispersal and exposure in Irvine Bay it is not possible to be more specific at the moment.

The nitrate enrichment of the upper Clyde amounts to 5 μg-at. NO_3-N/l. or less; this is probably enough to promote greater growth of phytoplankton as was found in the Loch Ewe experiments but here in addition there may be adverse factors such as increased turbidity, and toxic or inhibitory substances may be present which might reduce or reverse this effect. Further field work needs to be done to assess the actual overall effects on growth. No detectable effect (at 3 m) on the local nitrate concentration was observed when traversing the sludge dumping area off Garroch Head.

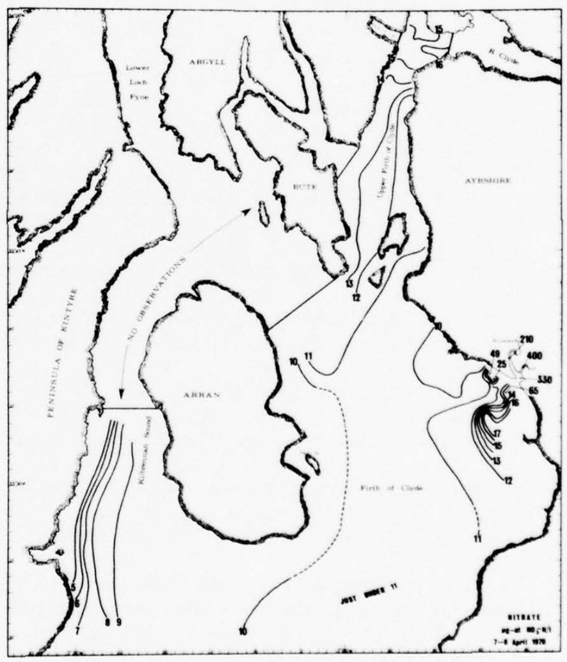


Fig. 2: Nitrate concentration in the Firth of Clyde.

Table I - Areas of High Nitrate

	Nylon effluent		Irvine-Garnock	
	Area km^2	NO_3 range μg-at NO_3-N/l	Area km^2	NO_3 range μg-at NO_3-N/l
Survey 1	1.05	12-40	1.75	12-33
2	1.05	12-27		flood tide
4	traces			traces
5	0.34	12-22		not sampled
6	2.44	12-23		high water
8	1.94	12-49	6.55	12-65
9	1.22	12-30	6.30	12-34

Chlorophyll, Phaeophytin and Productivity— Measurements of chlorophyll, phaeophytin and ^{14}C and O_2 uptake were made in Irvine Bay and offshore between Irvine Bay and Arran. The methods for chlorophyll and phaeophytin are given in Yentsch and Menzel (1963), Yentsch (1965) and ^{14}C productivity in Steemann Nielsen (1952) using the calibration method of Wetzel (1964). Even when the plume of effluent had been located at 3 m, water-bottle sampling was always uncertain in the neighbourhood of the nylon effluent and only one of the samples taken was later found to contain high nitrate. The results did not show marked differences between the inshore and offshore samples. There is no more than a slight tendency for inshore chlorophyll and ^{14}C productivity to be lower than offshore but the ^{14}C : chlorophyll ratios scarcely differ.

Plant growth at this time had not progressed beyond a typical low winter level.

Zooplankton—No plankton samples were obtained with the Gulf III from the shallow, most polluted, inshore waters.

In the areas sampled, copepods, which were approximately ten times more abundant than all the other small invertebrates combined, showed two main areas of abundance; one in the eastern half of the upper Firth of Clyde and one extending both east and west of the region south of Arran (Page 16). *Calanus* spp. and *Pseudocalanus elongatus* comprised over 75% of the copepod component at all but two stations, with *P. elongatus* forming over 70% in some samples, notably in Kilbrannan Sound and near the Island of Cumbrae. The total numbers of all other small invertebrates (Cladocera, Larvacea, cirripede nauplii, other crustacean nauplii and the larvae of bottom forms), when considered as a group, showed a similar distribution of abundance, the higher concentrations again occurring in the eastern half of the upper Firth of Clyde and the area south of approximately 55°33′N.

Of the chaetognaths, *Sagitta elegans* was the most abundant, but *S. setosa* did occur in small numbers, entirely northwards from 55°30′N. The latter latitude was also the southern limit of the egg capsules of the intertidal species, *Littorina littorea*. The euphausiids, *Thysanoëssa raschii* and *Meganyctiphanes norvegica*, were associated with the deep water off Arran as has previously been found by Mauchline (1960, 1966).

With the exception of the herring, little appears to be known of the distribution, within the Clyde, of the spawning products of the fish species found there. In the present samples the eggs and larvae of at least 16 species were found (see Table II) but it must be remembered that the species caught, and the proportions in which they are caught, will depend on the time of the survey in relation to the spawning periods and the duration of the larval phase.

The dispersal of the larvae of herring from the Ballantrae Bank spring-spawning grounds has been shown by Saville (1963) to be largely governed by the wind conditions over a short period subsequent to hatching. The pattern of larval herring distribution is similar to that reported for 5 April 1961 (Saville, 1965) for the area north of about 55°15′N. In that year predominantly strong westerly winds had resulted in a steady northwards movement of the larvae. In 1970 the first emergence of herring larvae over Ballantrae Bank was detected on 11 March and peak numbers over the bank appeared about the 16th (Baxter, private communication). Wind strength and direction data for the Mull of Galloway station (Meteorological Office, 1970) were used to compute longshore drift using 2% of wind speed over 4 hourly intervals during the 10-day periods following these dates (compare Dooley and Steele, 1969, for the same area). The results of these calculations indicate that the early larvae would have remained near the bank until the 16th during moderate easterly and northerly winds. Subsequently these, and the bulk of larvae which hatched about that

Table 2 - Fish Eggs and Larvae obtained from the Firth of Clyde with a Gulf III Sampler, 6 – 9 April 1970

	Eggs		Larvae	
Species or Group	Percentage frequency of occurrence	Average abundance No./100m^3	Percentage frequency of occurrence	Average abundance No./100m^3
Saithe/Norway Pout/Whiting	93	23	—	—
Saithe	—	—	44	6
Cod/Haddock	89	63	—	—
Cod	—	—	24	1
Dab	67	13	4	< 1
Rockling	48	6	—	—
Dragonet	44	3	—	—
Plaice	41	3	4	< 1
Argentine	30	1	—	—
Long Rough Dab	22	1	—	—
Lemon Sole	7	< 1	—	—
Butterfish	demersal	demersal	68	5
Herring	,,	,,	58	15
Gobies	,,	,,	16	< 1
Bullheads	,,	,,	8	< 1
Yarrell's Blenny	,,	,,	4	< 1

date, would have moved steadily northwards in a sustained spell of strong westerly winds. The predicted longshore drift for the early larvae was 32 km northwards, and 51 km for the main patch. These displacements would have conveyed the larvae into the region from approximately 55°25'N to Irvine Bay by late March, when those larvae near 55°35'N were liable to be carried shoreward, under the influence of the north-westerly and northerly winds, to the nitrate-rich region of Irvine Bay. However, since nitrate enrichment is likely to occur within only limited areas, the numbers of herring larvae affected were almost certainly very small in relation to the total population in the lower Firth of Clyde.

The predicted drift northwards and the suggested movement shorewards agrees fairly well with the observed distribution in the eastern half of the survey in April, while the work of Saville (1965) would suggest that those caught in the western half of the survey were also derived from Ballantrae Bank.

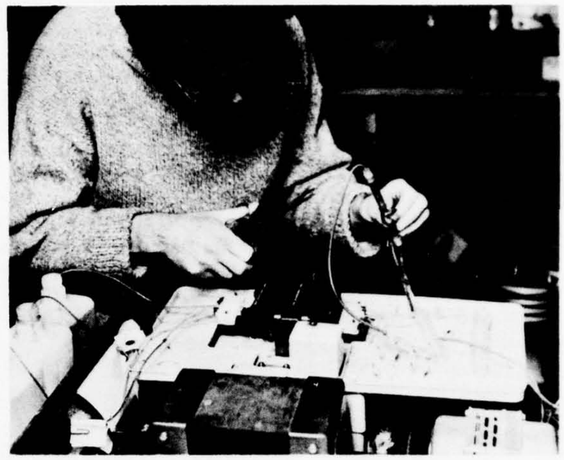
The eggs of saithe, Norway pout and whiting cannot be separately identified. Their numbers therefore have been pooled in our records, but in view of the absence of Norway pout and whiting larvae it has been assumed that the eggs of this type were predominantly those of saithe.

Spawning of the saithe is said to take place mainly in depths of 100-200 m (Wheeler, 1969), depths which, in the Firth of Clyde are largely confined to the deep areas off Arran. However, although saithe type eggs were found over most of the area surveyed they were more abundant in the same area as the herring larvae. Like herring (as a result of the circulation following spawning), the eggs and larvae of saithe were liable to be carried towards the area of high nitrates in Irvine Bay, but again the proportion of the population affected should be very small.

West (1970) has listed the areas in the Firth of Clyde where cod with roe have been taken in large quantities, namely, Girvan Bay, off the Heads of Ayr, south-west of Lady Isle, south of Arran (west of Pladda) and near Ailsa Craig. The delineation of the main concentrations of cod eggs during the present survey was complicated by the difficulty of separating early stages of the eggs of cod and haddock. (About 61% of the cod/haddock eggs were at stage II in their development but, on the basis that 75% of the stage IV eggs were recognisable as cod, it has been assumed that cod also dominated the earlier stages. No haddock larvae were found.)

In spite of the likelihood of cod spawning within the survey area the distribution of cod/haddock eggs was again—at least in part—similar to that of herring, and some eggs and larvae, from both local and more distant spawnings, could be brought into the area of nitrate enrichment.

Of the other species or groups which were present at the egg stage at more than 30% of the stations, only plaice would appear to have been largely free, at the time of the survey, from possible transport to Irvine Bay; plaice eggs were however present in the upper, nitrate-rich, Firth of Clyde. Only one other species occurred at the larval stage at over 30% of the stations—namely, the butterfish. A small number could have been transported into the nitrate-rich area. The eggs and/or larvae of the other species were of too sporadic occurrence to allow further consideration.



Using the Auto Analyser to measure surface nutrients.

SUMMARY

During March-April, 1970, a survey was made of certain physical and biological parameters in the Firth of Clyde in relation to areas of nitrate enrichment. As expected on the basis of previous observations, temperature and salinity varied only very gradually and tidal currents were found to be weak. Current measurements in Irvine Bay showed water movement to be parallel to the shoreline at almost all times, and closely related to local wind direction. However, an increased flow of the rivers Irvine and Garnock, following heavy rainfall, set up a secondary circulation in the bay for a short period. Offshore the circulation pattern was more complex, with a notable feature being the apparent entrainment inshore of the offshore waters, contributing to flushing of the Irving Bay area.

Compared to nitrate levels in the Firth of Clyde generally (5–11 µg-at NO_3-N/l), nitrate levels were higher (12–16 µg-at NO_3-N/l) in the waters of less than 33.0‰ in the upper Firth of Clyde, and much higher (12–65 µg-at NO_3-N/l) in the area of the nylon factory effluent and river discharges in Irvine Bay. At present it is not possible to determine the effects of these high nitrates, but it seems likely that limited areas of Irvine Bay reach levels of nitrate enrichment which result in an upset to the plant and animal life.

Probably largely as a result of the wind-induced circulation, zooplankton was found to be most abundant in the eastern half of the upper Firth of Clyde and in an area extending both east and west of the region south of Arran. This latter area extended also north-eastwards towards Irvine Bay where entrainment brought various species – including a number of fish eggs and larvae – towards the zones of high nitrate enrichment.

However, the numbers affected were almost certainly very small in relation to the total populations in the Firth of Clyde.

Further observations are required under a wide range of wind conditions.

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IMPERIAL CHEMICAL INDUSTRIES' INTERESTS IN THE CLYDE SEA AREA

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EXTENT OF INTERESTS

For almost a century explosives have been produced at Ardeer Works where today, ICI Ltd has a large industrial complex producing not only limited quantities of explosives but various chemicals and Nylon salts. Traditionally, the waste acids arising from explosives manufacture have been discharged untreated, either to the estuary of the Garnock or direct to the Clyde sea area where neutralisation by seawater is very rapid.

Since the early fifties the Brixham Laboratory of ICI has advised the Ardeer Works on the treatment and disposal of effluents and some limited investigations have been made of the fate of explosives dumped in the permitted area lying between Ardrossan and Arran. Over the years information has been acquired about the hydrography and ecology of coastal areas and the seabed in Irvine Bay. Many investigations of the effect of effluents have been made, largely those resulting from the closing down of many of the older chemical processes and the starting up of modern plant.

Today, the composition and volume of all discharges are carefully monitored and the toxicity of the wastes and specific effects on living organisms are evaluated by laboratory experiments at Brixham. From time to time, more general investigations of the inshore hydrography and chemistry of the receiving waters are made and a programme of investigation of benthic and littoral organisms has been introduced. As part of a comprehensive survey of many areas in the U.K., the metal ion contents of fish, invertebrates and sediments from Irvine Bay are being measured. Tables 1 and 2 and 3 overleaf give results of these analyses.

Chemical plant at ICI Petrochemicals Division's Nylon Works at Ardeer, Stevenston, Ayrshire (photo by courtesy of ICI Limited).

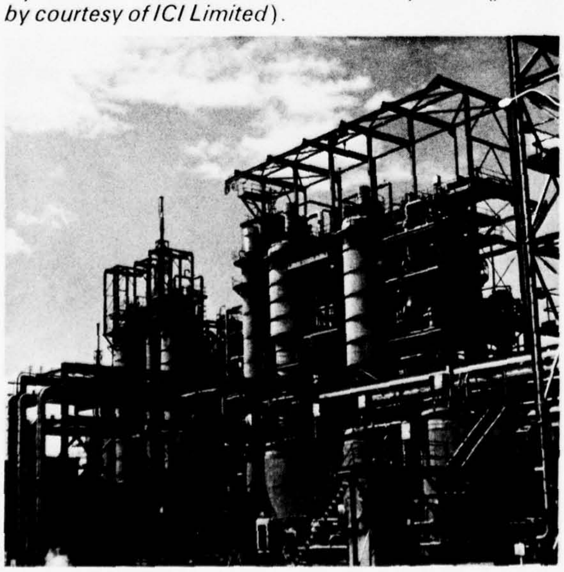

Table I Copper and Zinc levels in the Benthic Fauna of Irvine Bay - October 1970

Species		Dry weight g	Concentration (ppm dry weight) Copper	Zinc
Nephrops norvegicus	1	34.0	37.7	77.0
Eupagurus bernhardus	1	5.0	141.4	78.1
Eupagurus bernhardus	2	3.5	76.0	82.5
Eupagurus bernhardus	3	3.7	127.8	101.2
Eupagurus bernhardus	4	1.1	123.3	87.5
Buccinum undatum	1	16.7	42.7	167.0
Buccinum undatum	2	22.4	28.4	145.0
Buccinum undatum	3	28.9	20.9	352.0
Buccinum undatum	4	22.7	44.0	300.0
Buccinum undatum	5	32.7	32.3	450.0
Buccinum undatum	6	13.3	73.6	356.0
Buccinum undatum	7	3.1	30.9	240.0
Buccinum undatum	8	8.4	45.0	350.0
*Chlamys opercularis**	1	16.4	2.9	61.5
			(31.0)	(290)
*Chlamys opercularis**	2	11.8	7.1	87.5
			(30.0)	(235)
*Chlamys opercularis**	3	13.9	4.7	74.2
			(27.5)	(210)
Asterias rubens	1	4.4	11.4	196.8
Asterias rubens	2	3.0	15.9	321.2
Asterias rubens	3	5.8	11.3	106.2
Ophiothrix fragilis	1	1.33	12.8	103.0
Paracentrotus lividus	1	2.5	8.0	38.2
Paracentrotus lividus	2	0.6	6.8	69.2
Brissopsis lyrifera	1	2.1	13.5	80.0
Brissopsis lyrifera	2	4.0	13.0	85.0
Echinus esculentus	1	10.9	3.3	57.5
Echinus esculentus	2	18.4	4.7	42.6
Echinus esculentus	3	20.9	4.3	50.2
Pelonaia corrugata	1	0.7	20.6	131.2
Limanda limanda	1	3.8	11.0	98.7
Limanda limanda	2	8.7	8.5	61.2
Limanda limanda	3	5.9	29.7	66.2
Limanda limanda	4	10.5	39.9	91.5
Limanda limanda	5	18.4	18.7	107.2
Limanda limanda	6	12.1	13.2	95.2
Pleuronectes platessa	1	30.1	2.3	65.7
Pleuronectes platessa	2	20.9	3.2	68.5
Pleuronectes platessa	3	14.5	2.3	68.3
Pleuronectes platessa	4	14.1	3.3	60.0
Pleuronectes platessa	5	47.0	2.0	67.0

Values found in Control areas (ppm dry weight) (i.e. TORBAY)

Buccinum undatum (Cu 118.5 – 128.9. Zn 170.1 – 186.9)

Eupagurus bernhardus (Cu 45.4 – 132.7. Zn 64.2 – 78.0)

Asterias rubens (Cu 5.0 – 8.4. Zn 12.5 – 120.0)

Echinus esculentus (Cu 2.0. Zn 24.8)

Limanda limanda (Cu 2.7 – 9.4. Zn 42.6 – 52.9)

Pleuronectes platessa (Cu4.0 – 19.0. Zn 36.3 – 65.8)

**Bracketed figures refer to flesh only.*

STATE OF KNOWLEDGE

Searches of the literature and experience reveal a lack of relevant information about the hydrography, chemistry and biology of the Clyde sea area. For example, few measurements have been made of current velocities within Irvine Bay and there is no information about the rate of exchange of water between Irvine Bay and the main circulatory currents of the Clyde sea area. It would also be worthwhile to prepare synoptic charts of the nitrate content of these waters so that the extent of the nitrate containing effluents from Ardeer on productivity might be assessed. Clearly much further information is required if the effluent absorbing capacity of the entire Clyde sea area is to be assessed for the benefit of planners, dischargers of effluent and the public at large.

FUTURE INVESTIGATIONS

It is suggested that the following projects might usefully be undertaken:

1) Measurements of physical or biological parameters, at a number of hydrographical stations on a large scale grid covering the whole Clyde sea area so that a mathematical model may be constructed for the area. Such a broadly based study would show how, with limited resources for field work, the grid mesh might be reduced in size and a more detailed model constructed.

2) Agreed procedures and programmes of investigation should be introduced for monitoring marine organisms by the various laboratories so that the productivity for different areas may be compared and the significance of discharges of sewage and industrial wastes assessed by comparison of polluted and unpolluted areas.

Table 2 Copper and Zinc Levels in the Benthic Fauna of Irvine Bay March 1971

Species		Station	Dry weight g	Concentration (ppm dry weight) Copper	Zinc
Cyprina islandica		5	102.0	5.0	75.8
Acanthocardium echinata		5	22.5	3.0	25.2
Asterias rubens	1	Outfall area	19.1	8.5	208.8
Asterias rubens	2	Outfall area	31.8	11.2	213.0
Asterias rubens	3	Outfall area	58.5	7.0	184.8
Asterias rubens	4	Outfall area	15.5	7.0	177.3
Asterias rubens	5	Outfall area	21.4	9.0	235.8
Asterias rubens	6	Outfall area	12.7	11.5	220.8
Amphiura filiformis	1	1	5.3	23.2	334.0
Amphiura filiformis	2	2	4.5	75.0	320.0
Amphiura filiformis	3	3	1.5	13.1	579.0
Amphiura filiformis	4	4	4.3	23.7	119.0
Amphiura filiformis	5	5	5.6	11.8	—
Brissopsis lyrifera	1	1	4.2	16.4	80.0
Brissopsis lyrifera	2	2	1.2	29.2	570.0
Brissopsis lyrifera	3	3	1.6	33.1	640.0
Brissopsis lyrifera	4	4	4.8	15.3	1310.0
Brissopsis lyrifera	5	5	8.5	4.2	52.0
Pelonaia corrugata	1	1	1.6	27.2	130.0
Pelonaia corrugata	2	3	0.9	42.2	550.0
Pelonaia corrugata	3	4	1.4	64.2	368.0
Pelonaia corrugata	4	5	3.2	32.8	170.0

Table 3 Metal Ions (ppm dry weight) in sediments offshore Irvine Bay

Sample No.	1	2	3	4	Torbay sediments
Copper	18.3	13.3	13.6	13.3	10.0
Zinc	81.5	72.3	71.5	69.8	35.0
Chromium (total)	60.3	53.2	53.8	57.0	20.0
Mercury	0.4	0.4	0.4	0.2	0.1

Table 4 Metal Ions (ppm dry weight) in sediments from Shoreline in Irvine Bay

Sample No.	1	2	3	4	5	6
Copper	23.3	16.9	17.4	16.6	14.9	13.3
Zinc	73.6	62.9	58.9	62.4	63.7	59.8
Chromium (total)	14.2	26.9	20.5	18.9	17.4	20.7
Mercury	0.02	0.02	0.02	0.05	0.04	0.07

POLLUTION IN THE CLYDE

Clyde River Purification Board, East Kilbride, Glasgow.

INTRODUCTION

Nine river purification boards were established following the implementation of the Rivers (Prevention of Pollution) (Scotland) Act 1951. In the highlands and in the catchments of the north and south Esk, county and large burgh councils carry out the functions of the Act. The area of the Clyde River Purification Board comprises the catchment of the River Clyde and includes the estuary, the upper Firth, Gare Loch, Loch Long, Holy Loch, Loch Striven, Loch Riddon and Loch Fyne. About 45% of the population of Scotland lives within the area.

The main duties of the Board, as laid down in the 1951 Act, are 'to promote the cleanliness of the rivers and other inland waters and the tidal waters in their area and to conserve so far as practicable the water resources of their area'. The powers to control pollution are broadly similar to those available to English and Welsh river authorities, but there is no Scottish equivalent of the 1963 Water Resources Act. New and existing discharges of sewage and trade effluents are controlled by consent. Improvements are achieved by the progressive imposition of standards, in accordance with a scheme of priorities, thus stimulating investment in treatment plants and in more effective systems of water usage. 3,761 consents have already been issued by the Clyde River Purification Board: there have been no appeals to the Secretary of State against their implementation.

Since the tidal water order for the Clyde came into force, giving the Board similar powers over discharges to the estuary and the sea as to inland waters, the licensing system and the expertise of the inspectorate in defining realistic standards and time-scales for improvements has been found to be equally applicable.

The Board has been faced with many urgent pollution problems in an area which is changing as rapidly as any in Britain, involving the rehabilitation of many rivers which have been heavily contaminated since the first industrial revolution and the safe-guarding of others which are now being affected by new development. A particular cause for concern was the condition of the upper estuary, where complete absence of dissolved oxygen during dry weather was leading to foul odours and corrosion of equipment, including heat exchangers on ships. Many noteworthy improvements to both inland streams and tidal waters have been achieved during the last few years and very few reaches have deteriorated, in spite of the considerable increases in the volumes of wastes being discharged and their growing complexity.

A far-reaching scientific programme has enabled the Board to accumulate more data on river flows, tidal current movements, water quality and bio-assay, enabling decisions to be made on new problems as they arise. Close liaison is maintained with planning authorities and developers; and the Board has been able to increase its influence on the siting of new communities and industries.

INDUSTRIAL DEVELOPMENT IN THE TIDAL WATERS OF THE CLYDE DURING THE LAST 25 YEARS

Over this period, industrial development around the Clyde estuary has been centred mainly on Glasgow and its immediate hinterland. There has been a 50% increase in water consumption during this period, from 295 litres/head/day to over 450 litres/head/day. This increase has been caused largely by industrial demands and it has resulted in a corresponding increase in the volumes of effluents discharging to the estuary.

The water-using industries involved include distilleries, textile manufacturers, carpet manufacturers, pigment manufacturers, paper mills, tyre manufacturers, tanneries, food-processing firms, metal finishers and oil refiners. Most of the industrial discharges are made to local authority sewers, but many are largely unpurified when they reach the estuary due to inadequate sewage treatment facilities. Only settlement is provided at three major sewage works on the estuary, and perhaps because biological treatment processes are not threatened, the two local authorities concerned have not enforced control of trade effluents discharging to their sewerage systems. These sewage works can, therefore, be an escape route to the estuary for discharges of heavy metals and toxic organic materials. This situation will inevitably improve when modernisation of the sewage works, now required by the Board, is completed.

Industries with direct discharges to tidal waters include electricity generating stations, a large grain distillery, paper mill, textile manufacturers, a metal plating firm and a pigment manufacturer.

The unsatisfactory condition of the estuary has resulted in the re-siting lower down the Firth of a large electricity generating station which the South of Scotland Electricity Board wished to locate on the

The Yoker Power Station on the Upper Clyde Estuary (photo by courtesy of CRPB)

estuary at Bishopton; the large discharge of cooling water from the station would have extended the anaerobic zone of the estuary to the River Leven and this would have adversely affected the movement of migratory fish to Loch Lomond. The establishment of other water-using industries on the estuary has also been discouraged by the lack of river water of a satisfactory quality.

It is considered that much of the major development during the next few years will be on the Ayrshire coast and this will inevitably pose new problems of pollution control. Investigations are already proceeding in connection with the establishment of oil refineries and a steel complex.

POLLUTION OF THE TIDAL WATERS OF THE CLYDE

The objectives of the Clyde River Purification Board in respect of the waters of the firth are (a) to secure the economic rehabilitation of already seriously polluted stretches of water, (b) to ensure that currently class areas are maintained in that condition and (c) to provide advice and guidance at the planning stage of proposed future developments. To achieve this the Board must have adequate data on the hydrography, chemistry and biology of the tidal waters and on the volume and composition of the effluents being discharged.

PROBLEMS IN THE CLYDE AREA

Apart from radioactivity which is not the direct concern of the Board, five main classes of marine pollutant are identified. These are:

Oxygen consuming materials including domestic sewage and certain industrial effluents, for example distillery wastes. This type of pollution is the most obviously harmful in the area, producing anaerobic conditions in several miles of the upper estuary, and surface and beach contamination to a greater or lesser degree in the firth and sea lochs. Considerable progress in the rehabilitation of the upper estuary has already been achieved and alternatives for effecting further improvements have been determined by mathematical modelling techniques using a computer (Mackay and Waddington, 1970; Mackay and Gilligan, 1971). Following the removal of floatable solids, satisfactory disposal of sewage and many other effluents can often be achieved on open coastlines by efficient dispersion from outfalls taking advantage of prevailing currents. The Board undertakes investigations into the siting and form of such outfalls.

Oil pollution is an obvious problem in the Clyde area. The number of incidents reported increases annually and the Board co-ordinates other interests to tackle incidents. A communications network has been set up and any oil slick observed by the various reporting agencies is immediately notified to a message receiving centre which is manned continuously. The reporting agencies include civil airlines, shipping, coastguards, lighthouse-keepers, the police and the Royal Navy.

If the oil can be dealt with at sea, the regional co-ordinating officer requests the Royal Navy to use their specially equipped vessels to disperse the oil with detergent. If the oil slick comes ashore the local authority affected takes the necessary action to remove or disperse the oil. There is close liaison with the Nature Conservancy and with fishery officers to determine action which can safely be taken against oil on sites of importance to wildlife and fisheries. In the event of a major oil spill, the regional co-ordinating officer directs operations from an emergency control centre at Greenock.

Trace organic substances are discharged from a variety of sources, but in particular the carpet manufacturing industry makes use of pesticides, including dieldrin, as mothproofing agents. For several years specimens of mussels from five points within the Board's area have been sent to the Freshwater Fisheries Laboratory of the Department of Agriculture and Fisheries for Scotland. Fish from the Firth of Clyde are also checked at six monthly intervals for levels of pesticides. Pesticides in effluents are being assayed in the Board's laboratory at Rivers House.

Polychlorinated bi-phenyls have been the subject of intensive study by the Board since they were suspected of association with sea-bird mortalities two years ago. The principal British manufacturer has agreed to severely curtail supplies to categories of users who are not in a position to stop leakage to the environment. The efficiency of this approach is being tested by a comprehensive monitoring programme undertaken by the Board, of sludges which are dumped at sea and which had previously been found to contain significant concentrations of PCB's.

Toxic metals including lead, copper, zinc, cadmium and mercury are discharged to the tidal waters of the Clyde and investigations are being made of biological assay and food chain concentrations. The Board is co-ordinating a research programme into the source, distribution and dispersion of toxic metals in the marine environment, from the head of the estuary to the Isle of Arran.

Thermal pollution from coal and oil fired power stations is being investigated by the Board. The studies carried out by the Board which led to the re-siting of the 2,400 MW power station have been described above.

THE MAIN POLLUTION PROBLEMS

Pollution Problems in the Clyde Estuary—The upper estuary, extending from the tidal weir in the centre of the city of Glasgow to a point 24 miles seaward at Greenock, is undoubtedly the most highly polluted stretch of water in the Board's area. The upper estuary receives direct discharges from two major sewage works and several highly polluted rivers. Anaerobic conditions occur for several weeks in each year, often for several miles. The main pollutant is domestic sewage, but the estuary also receives a large number of industrial effluents, separately or mixed with sewage. Major management problems may be summarized as follows:

Anaerobic conditions produce smell and are a nuisance in residential areas.

The valuable salmon fishery of the Loch Lomond catchment and the River Leven is threatened by the heavily polluted zone at present terminating just above the Clyde/Leven confluence.

A projected 2,400 MW station could not be sited adjacent to the upper estuary because of the further oxygen depletion which would have resulted from the discharge of cooling water.

Failure of ships' condenser tubes resulting from corrosion by heavily polluted water has occurred in the upper estuary.

A reduction in the average freshwater input to the estuary as a result of a major new water supply scheme at Loch Lomond.

The retention of wastes in the estuary would be further increased by narrowing the channel if land were reclaimed for industrial development.

The main problems are those associated with oxygen depeletion and considerable effort has been devoted to determining the most efficient and economical methods to restore dissolved oxygen content to satisfactory levels. The techniques adopted and the results achieved are summarized by Mackay and Fleming (1969) Mackay and Waddington (1970) and Mackay and Gilligan (1971).

A rational programme for economic rehabilitation of the estuary to any desired level of dissolved oxygen has now been drawn up. A considerable reduction in the polluting load has already been achieved and this trend should continue during the next few years.

The estuary is regularly surveyed for benthic fauna to measure changes in its condition. Metals in deposited solids are routinely determined.

POLLUTION PROBLEMS IN THE FIRTH OF CLYDE

This area includes all the coastal waters, other than the upper estuary and sea lochs, which come within the Board's jurisdiction, and also a small area (Garroch Head) which lies beyond the controlled waters. The Garroch Head area has been used for sludge dumping by Glasgow Corporation for almost seventy years: it has been investigated by the Board for two reasons. The first is that dumped material may be carried into, and exert its effects on, the waters for which the Board have responsibility. The second, that no other organisation had investigated the problem. This position has now changed and several organisations undertake programmes in the area. The Board's preliminary survey showed little evidence of gross pollution, but indicated several areas of research where further investigations would be justified.

Some of this work is specialized, and the Board has developed joint programmes with experts in the analytical field, such as Professor Webb, Department of Geochemistry, Imperial College (heavy metals) and Dr Bogan, Department of Veterinary Pharmacology, University of Glasgow, (organochlorines). Mackay and Topping (1970) give some results of preliminary work in this field. Results of more detailed study have been published by Mackay *et al* 1972.

Although there is little evidence of eutrophication in the outer firth or sea lochs, the Board have considered it advisable to undertake a programme of measuring nutrients levels so that any changes in the future will be recognized. Accordingly, a series of 13 stations between the upper estuary, the Tail of the Bank, the Largs Channel and Arran, are visited at approximately monthly intervals and the waters sampled at a series of depths. Analyses are performed for nitrate, phosphate, silicate and metals.

One of the major problems in the outer firth is the distribution and dispersion of discharged effluents. Because of the complex water circulation pattern of the area many effluents can be carried rapidly from their sites of origin. Considerable progress has been made in establishing circulation patterns in the outer estuary. Although conservative effluents capable of being re-concentrated are perhaps of more fundamental importance, it is nevertheless true that the majority of discharges to tidal waters consist mainly of domestic sewage and biodegradable trade wastes. For these, the problem of pollution control in open waters is often reduced to one of adequate dispersion, ensuring that no unsightly deposits appear on beaches or on the surface and that animal and plant communities are not deprived of oxygen or light, or smothered by deposited sediments. To this end, the estuary survey team have devoted a considerable proportion of their efforts to studies of outfall layout and siting.

POLLUTION PROBLEMS IN THE SEA LOCHS

Many of the sea lochs of the west coast of Scotland are fiordic in character, long, narrow, steep sided and very deep. They present some difficult problems for water pollution control:

Surface borne material – Sewage, plastics and oil tend to be retained and accumulate within the lochs. This can lead to gross pollution of the shoreline because the sea lochs are often important recreational areas.

Oil pollution – Loch Long serves as a major oil terminal with 300,000 ton tankers penetrating 45 km inland along a busy and narrow channel before discharging.

Toxic materials – Several of the sea lochs, with little input from rivers, have very long retention times. Under these circumstances, the use of pesticides or fungicides may lead to a dangerous concentration of such materials.

Organic waste – Effluents with a high oxygen demand can have serious effects when discharged to the restricted and often stratified waters of the sea lochs. Surveys have shown that the capacity of most of these lochs to receive organic wastes without serious oxygen depletion is surprisingly limited. A comprehensive programme to determine the capacity of each loch has been undertaken, in view of possible industrial development. One such study has been published by Mackay (1969).

RADIOACTIVE POLLUTION

The Gare Loch and Holy Loch are bases for the British and American nuclear submarine fleets respectively, and the accidental discharge of radioactive material provides an additional hazard. The Board, therefore, maintains a very close liaison with the Ministry of Defence, which is responsible for monitoring these areas.

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A REVIEW OF STUDIES ON THE MICROORGANISMS OF THE CLYDE SEA AREA

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INTRODUCTION

Relatively little microbiological work has been done on the Clyde sea area, or, if done, no reports appear in available literature. The most detailed of the studies reported are those from the former Royal Technical College and present University of Strathclyde, on the taxonomy and distribution of yeasts and those from the Millport Marine Station on phytoplankton. The latter work is reviewed elsewhere in this Report and so is not included here. Reported bacteriological studies on the estuary have been carried out almost exclusively at the former Royal Technical College. Most of this work is simply an enumeration of bacteria in water and sediment samples, but attempts were usually made to relate the results to the areas.

STUDIES ON YEAST ISOLATED FROM THE MARINE ENVIRONMENT

Reports on the yeast flora of the Clyde estuary were made by the following:—Ross (1963); Ross and Morris (1965); Lloyd (1970); Lloyd and Morris (1971); Lloyd, Morris and Smith (1971); Bruce (1970). The yeasts identified in these studies are shown in Table 1. The relationship of yeasts found, to yeasts isolated from marine materials elsewhere are discussed by Morris (1968). Ross (1963) compared the yeast flora isolated from fish caught in the Atlantic, North Sea and Clyde estuary, differences in distribution were noted, but their significance could not be assessed.

Isolates from marine fish were found to comprise eight genera, *viz. Debaryomyces, Torulopsis, Candida, Rhodotorula, Pichia, Trichosporon, Cryptococcus* and *Pullaria*. Of these genera only *Debaryomyces, Candida, Torulopsis* and *Pichia* were isolated from fish caught in the Clyde estuary. Notable features of the isolates from the Clyde estuary were the high incidence of *Torulopsis* spp. mainly *T. inconspicua* (var.) and the absence of *Rhodotorula* spp. and *Debaryomyces subglobosus,* both of which were isolated from fish caught in the other two areas. Two strains could not be assigned to generic rank.

Although the study mainly concerned the yeast flora of marine fish, several water samples were examined. These were collected from White Bay, off the Cumbraes at a depth of 40–60 metres; as with fish samples, *Debaryomyces hansenii* (*kloeckeri*) predominated. Apart from this similarity, the yeast flora of fish and water was quite distinct. Other than *D. hansenii* (*kloeckeri*) the yeasts isolated from water of the Clyde estuary comprised: *Metschnikowia*, *Cryptococcus* and *Trichosporon* species.

Lloyd (1970) isolated and identified yeasts from Clyde estuary sediments. *Debaryomyces hansenii* was again commonest and accounted for over 60% of the isolates. *Rhodotorula* spp. were also found, but were not found on fish or in water by Ross (1963). By contrast *Torulopsis* spp. and *Candida parapsilosis* were common on fish but were not found in the sediments. *Candida* spp. isolated from

Table I Yeast species isolated from various sources in the Clyde Estuary

Yeast species	Yeast from fish	Yeast from water	Yeast from sediment	Psychrophilic yeasts from fish and other macro-fauna Bruce (1970)
	Ross (1963)		Lloyd (1970)	
Debaryomyces kloeckeri now	●	●		
Debaryomyces hansenii synonymous			●	●
Candida parapsilosis	●			
Candida pelliculosa			●	
Candida mycoderma			●	
Candida tropicalis var. *lambica*				●
Candida scotti				●
Candida spp.				●
Torulopsis inconspicua (var.)	●			
Torulopsis famata	●			●
Torulopsis candida	●			
Torulopsis sake				●
Cryptococcus diffluens		●	●	
Cryptococcus albidus		●	●	
Cryptococcus laurentii		●		●
Rhodotorula glutinis				●
Rhodotorula glutinis var. *rubescens*			●	
Rhodotorula mucilaginosa			●	
Rhodotorula informominiata				●
Pichia membranaefaciens	●			
Metschnikowia krissii		●		
Trichosporon cutaneum var. *multisporum*		●		
Unclassified yeast-like fungus			●	

the sediments do not appear to be common inhabitants of the marine environment, and the presence of these species may be caused by terrestrial contamination. An interesting yeast-like organism was isolated which appeared to have a unique morphology.

Bruce (1970), in work similar to Ross (1963), compared the yeast flora of fish and various other macro-fauna from the Clyde estuary. Samples were collected from two areas off Great Cumbrae and the North Sea. While sample sources and isolation techniques were similar in both studies, Bruce selected only psychrophilic yeasts and the differences in the yeast flora shown in Table 1 may be caused by this. Bruce (1970) and Lloyd (1970) also studied the physiology of their isolates.

Rhodotorula informominiata was found by Bruce (1970) in the Clyde estuary but not in the North Sea, and this is in agreement with the findings of other studies that this yeast most frequently exists in the inshore and estuarine areas. *Torulopsis sake* and also *Candida tropicalis var. lambica* were found only in the Clyde estuary and Bruce (1970) suggested that these species may owe their presence to land drainage and pollution.

BACTERIOLOGICAL STUDIES

Ellis (1925) attempted to determine whether the blackness of sand observed at various localities of the Clyde estuary was related to sewage pollution. The various areas examined and their range of bacterial counts per g of sand, estimated by plating were as follows: Ardmore, North Bay, 10×10^3 to 120×10^3; Roseneath Bay, 40×10^3 to 3×10^6; Sandbank on the Holy Loch, 30×10^3 to 2×10^6; Lunderston Bay, 40×10^3 to 600×10^3. *Bacillus coli* (*Escherichia coli*) was not detected in any sample from these areas. Blackening of sand with similar microbial counts was also observed at Blackwaterfoot in Arran, an area remote from sources of pollution, thus Ellis concluded that there was no direct connection between blackening of sand and sewage pollution. Ellis went on to demonstrate that formation of blackened layers beneath the sediment surface was related to reducing conditions causing production of ferrous sulphide from iron salts in the sand.

Subsequently, Ellis (1926) worked on sulphur bacteria and gave an account of the life history of a new genus, *Thioporphyra volutans* (Ellis) isolated from the shores of the Clyde estuary. Later Ellis and Stoddart (1930) followed the chemical changes caused by continued development of *Thioporphyra volutans* in shallow pools of seawater. Ellis (1924) gives a detailed description of *Beggiatoa alba*, a sulphur bacterium frequently detected in various land-locked waters of the Clyde; it was suggested that sometimes this organism was a useful indicator of sewage pollution.

Ellis (1929) examined the shore and shore water of the estuary for bacteria at Port Glasgow, Greenock and Gourock, where considerable pollution visibly occurred through discharge of untreated sewage. The sheltered areas such as Gourock Bay, East India Harbour and Scott's Fitting-Out Basin in which sewage was observed to accumulate were studied and the bacteriological content of various sewage outfalls and stream discharges entering the Clyde at these places estimated. Plate counts of saprophytic bacteria, from the shorewaters adjacent to the three towns, were on average five times greater (approximately 10×10^3 per ml) than counts from water in the middle of the Firth (approx. 2×10^3 per ml). However, at a number of points along the shore there were various highly polluted back waters and counts of up to 5×10^6 bacteria per ml were recorded. Examination of sediments in these areas gave bacterial counts of up to 4×10^6 per g of sediment for blackened sand and up to 25×10^6 per g for certain dark coloured muds.

Ellis (1932) estimated the extent of dilution of the microbial population of untreated sewage when discharged into the sea from effluent pipes at Ayr and Rothesay. The number of saprophytic bacteria (gelatine and agar plate counts) and of the number of coliform bacteria (taurocholate-agar plate counts) in sea water samples at various distances from the point of discharge were estimated. From the results Ellis concluded that dilution was well within the standards set by the Eighth Report of the Royal Commission on Sewage Disposal (1912).

Lloyd (1930) investigated the vertical, seasonal and diurnal variations in bacterial numbers in the water of Loch Striven, Loch Long and off Greenock. Cumbrae Deep which served as the dumping ground for Glasgow sewage (activated sludge) was also studied. Saprophytic bacteria and intestinal bacteria were counted in water samples from these areas. It was concluded that Loch Long water contained more bacteria than that of Loch Striven and that both lochs were little polluted. Much higher counts mainly of intestinal bacteria were recorded in water samples collected from the deepest part of the river channel at Greenock, and similar results were obtained with samples taken from Cumbrae Deep, showing that sludge dumped there markedly affected the bacterial content of the sea water.

Lloyd (1929) reported an organism isolated from the water of Loch Striven, as a hitherto undescribed chromogenic bacterium related to *Bacillus salmonicida*. McCallum (1969) reports studies in the Clyde estuary on bacterial species indicating faecal pollution. Presumptive coliform tests and enterococci isolation were made on water samples from various sites and depths in the estuary. The presumptive coliform test was positive for all samples examined, but the coliforms isolated from such samples were not always *E. coli*. Enterococci were found only in the upper reaches of the estuary and large numbers only at Rosneath. *Streptococcus faecalis* was isolated from all samples positive for enterococci and McCallum thought laboratory experiments showed these organisms to be better indicators of faecal pollution in coastal waters than *E. coli*.

In addition to the published studies already mentioned, A. Gilmour of the University of Strathclyde has determined the bacterial flora of estuarine water used for a fish farming project at Hunterston (White Fish Authority). The water examined originates from the estuary, but is lightly chlorinated and used for cooling in the Hunterston power station

before entering the fish tanks. Chlorination clearly reduces the value of the study in the present context, but the flora identified probably reflects to some extent the original estuarine population. The bacterial species isolated, comprise the following:— *Pseudomonas* Group IV, *Pseudomonas* Group II, *Vibrio*/anaerobic *Aeromonas, Flavobacterium/Cytophaga* and possibly another *Myxobacteria, Moraxella, Achromobacter/Alcaligenes/Agrobacterium,* unidentified Gram-positive cocci.

In addition to the work of Ellis (1925, 1929) already referred to, Lloyd (1931) and, more recently, Anderson and Meadows (1969), report studies on the bacteriology of sediments in the Clyde estuary. Lloyd (1931) examined sediment samples from Loch Striven Head, Clapochlar, Carroch-Corrie and Kames Bay. Bacterial counts of the surface of the sediments in these areas did not differ markedly and ranged from 70×10^3 to 300×10^3 per g dry sediment. At all sampling areas the bacterial counts decreased for samples taken from below the sediment surface. The predominant organisms found were water bacteria of the *Achromobacter* and *Chromobacterium* types and large spore forming bacilli similar to common soil bacteria.

Anderson and Meadows (1969) estimated the number of bacteria attached to the surfaces of sand grains from intertidal beaches between Wemyss Bay and Troon on the Ayrshire coast. Counts estimated by plating procedure varied from 2 to 241×10^3 per g of dry sand or otherwise expressed as 0.2 to 40 per mm^2 of sand grain surface.

STUDIES ON BLUE-GREEN ALGAE AND SIMPLE MICROALGAE

Meadows and Anderson (1966, 1968) developed a simple staining method to observe, *in situ,* the microbiological flora of sand grains from the Ayrshire coast and Etterick Bay (Island of Bute). The work provided a general description of the distribution of micro-organisms on the surface of sand grains. The following blue-green algal genera were tentatively identified: *Merismopedia, Anabaena, Microcystis* and possibly *Lyngbya.* In earlier work by Stewart (1961) three species of blue-green algae, *Calothrix scopulorum, Nostoc entophytum* and *Oscillatoria brevis* were isolated from the Ayrshire coast. Stewart (1961) also made extensive physiological and biochemical studies on these organisms and showed that both *C. scopulorum* and *N. entophytum* were able to fix nitrogen.

Meadows and Anderson (1968) used this method to estimate diatom numbers attached to sand grains from littoral and sublittoral zones of Etterick Bay. The diatoms and, in general, the total microbial population, were sparse towards high water, but differed little as between lower littoral and sublittoral sands. In depth profiles, the microbial flora usually altered only slightly to depths of 15 cm below the sediment surface although occasionally in some sampling areas dramatic changes in the microbial flora were seen within a few millimetres.

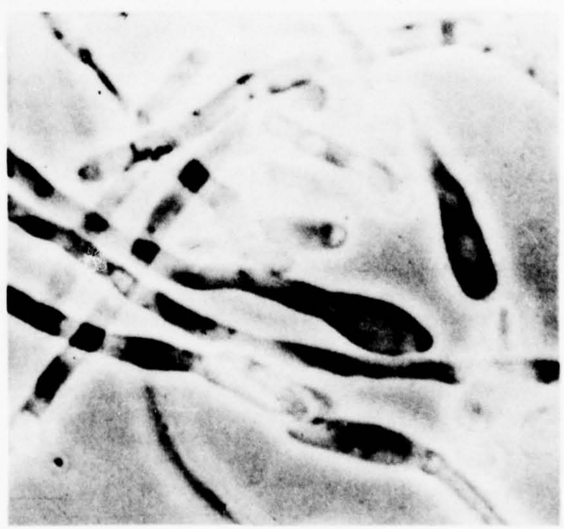
The microalgal flora of supralittoral brackish rock pools on the island of Cumbrae have been studied by Droop (1955). Several new species and varieties found in these pools were described and details given of their cultivation. They comprise the following:

Chlorophyceae, *Nannochloris oculata* and *Brachiomonas submarina* var. *pulsifera.*
Cryptophyceae, *Hemiselmis virescens.*
Crysophyceae, *Syracosphaera elongata, Microglena arenicola* and *Mallomonas epithalattia.*

The typical dominants of these pools other than the species described above were *Oxyrrhis marina, Monochrysis lutheri, Chlamydomonas pulsatilla* and *Platymonas* spp.

A mixed colony of blue-green algae on a sand grain surface, Clyde Estuary. The chains of cells are Anabaena *sp., and the tetrads of cells are* Merismopedia *sp.* (*Meadows and Anderson, 1968*).

An unidentified fungus isolated from the Clyde Estuary. In the initial stages of growth the cells are elongated yeast forms. These later develop into pleomorphic coenocytic mycelia, shown here.



MICROORGANISMS OF THE CLYDE SEA AREA

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PLANKTON IN THE FIRTH OF CLYDE

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The general outline of plankton periodicity throughout the year is fairly well known due to the long term studies carried out by the SMBA whilst at Millport.

Phytoplankton—A spring 'outburst' is an annual feature, although its timing and size will vary from year to year. The dominant diatom is almost always *Skeletonema costatum* (often making up to 92 or 99% of the diatom population). Occasionally *Thalassiosira* spp. will dominate, and these species are usually always present as subsidiary components in a *Skeletonema*-dominated outburst. *Ditylum brightwellii* is another diatom often seen in relatively small numbers later in the season. The spring sequence for the Firth of Clyde seems to be fairly typical of the Clyde Sea area. In many years (for example, in 1924–26 and later) two 'waves' of *Skeletonema* were observed, with the first 'wave' occurring usually between mid-March and early April. In Loch Striven the *Skeletonema* dominance in 1924 was such as to resemble almost a 'pure culture' of the organism. The timing and nature of these spring 'outbursts' have been regularly documented since 1944.* Thus the *Skeletonema* increase was observed in March 12th samples in 1944, whilst in 1945 it was timed as one week earlier. Much the same pattern emerged in 1946 and 1947, both in the Firth of Clyde and Loch Striven. In this second locality the *Skeletonema* growth followed a period of abundant sunshine with accompanying low air temperatures; this early March growth of *Skeletonema* usually ceased by mid-April. Whilst in 1950 the spring sequence remained much the same, in 1951 *Skeletonema* showed no appreciable growth until mid-May and was preceded by a small peak of *Coscinodiscus* sp. and *Chaetoceros* sp. in early March followed by a second *Chaetoceros* peak in mid-April. In the following year the main growth period of *Skeletonema* was in late April. Relatively small variations in phasing were observed in subsequent years. The exception was 1958 when, following a cold winter and a protracted period with cold easterly winds, a *Coscinodiscus* sp. was a prominent representative of the spring growth followed by *Thalassiosira* sp. and *Chaetoceros* sp. which were both present in large numbers through March and on into May. *Skeletonema* was not a prominent component until mid-April, coincident with calm seas and sunny weather. In subsequent years (until 1962) the sequential pattern was as first described.

The summer months are characterized by a series of phytoplankton increases, very occasionally of a greater magnitude than the spring increase but usually smaller. Dinoflagellates are most abundant in the summer and autumn, with occasional short-term 'blooms' by *Peridinium* and *Ceratium* spp. In 1967, species of *Peridinium Ceratium* and *Dinophysis* were the dominant organisms, their time of abundance coinciding with the maximum sea temperatures for the year but lagging by 1–2 months behind the maximum annual irradiance. Diatoms prominent in the summer include *Leptocylindrus danicus*, *Rhizosolenia setigera*, *Cerataulina* sp., *Chaetoceros* spp., *Eucampia zodiacus* and *Nitzschia seriata*. Subsidiary 'blooms' of a coccolithophorid organism have been observed in the summer months on occasions.

The dinoflagellates are abundant in the summer and often remain so until late in the autumn; they are accompanied by *Skeletonema*, *Nitzschia* and *Leptocylindrus*. In some years these last two species have been the dominant diatoms, with the occurrence of *Thalassiosira* sp. a prominent feature of the October flora. Silicoflagellates are found in small numbers in most seasons, but frequently are noticeably more abundant in the autumn months.

The winter diatom flora has been described as consisting mainly of species of *Thalassiosira*, *Biddulphia* and *Coscinodiscus* with small numbers of dinoflagellates.

Littoral diatoms: Although these make a negligible contribution to the overall primary productivity, their seasonal periodicity is a well marked feature of the annual turnover of the flora. Observations made on diatom settlements on glass slides in the region of Keppel Pier have shown that between January and mid-June 1947 these settlements were dominated by *Schizonema ramosissima* and *S. grevillei*. Following this there was a clear succession of attached and epiphytic diatoms throughout the littoral zone. In Loch Striven the two *Schizonema* spp. were again prominent between February and March. A *Rhabdonema* sp. was then present in some quantity, followed again by *Schizonema* spp. In April *Fragilaria striatula* and *F. oceanica* were prominent components, whilst other littoral diatoms were present in small numbers.

Zooplankton—*Microzooplankton:* Tintinnids are present all the year round in small numbers, although *Favella serrata* may be found in huge numbers in July and August on occasions. A *Mesodinium* sp. has been known to produce a 'red tide'.

Zooplankton: Breeding of copepods and of many benthic invertebrates begins about the time of the spring diatom increase and from then on throughout the summer planktonic larvae are abundant. Correlations have been observed with the timing of the diatom spring 'outbursts' and the spawning of *Balanus balanoides* and the occurrence of 'ripe' females of the copepod *Calanus*. Barnacle larvae have been observed in enormous numbers at the time of the spring diatom outburst. The copepods are the most important holoplanktonts both in overall numbers and their basic significance as food for fish. *Calanus* spend the winter in the pre-adult stage in deep water. Moulting to adult phases occurs in January and February and spawning then follows from late March to early April, the onset depending on the date of the spring diatom increase. First generation spawning is seen in May and there are then one or two more spawnings during the summer.

* *The SMBA observations on which this discussion is based were made on samples of sea water, centrifuged and unconcentrated, not on tow net samples.*

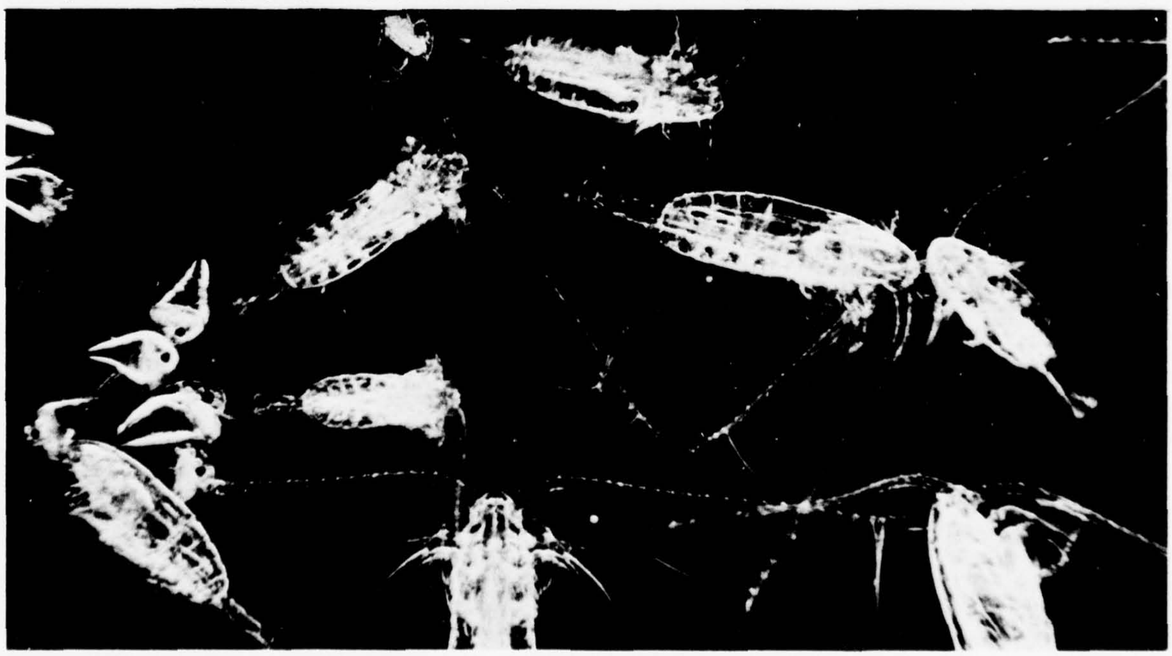
Breeding is usually over by the end of August. Maximum numbers are seen with the 1st or 2nd generations. *Pseudocalanus* and *Microcalanus* both follow much the same growth and breeding cycle as *Calanus*. *Centropages* and *Temora* are usually less abundant, breeding in the summer and then probaby overwintering as resting eggs. *Acartia* and *Oithona* breed in the summer and, possibly, in the autumn. This general picture can be subject to great variation from year to year. Ctenophores (mostly *Bolinopsis infundibulum*) appear in numbers in May and are usually abundant for some weeks; they may be so numerous in some years that they probably destroy a large proportion of the *Calanus* stock. *Calanus*, usually present in large numbers all the year round, may almost disappear for no obvious reason perhaps because the course of the spring diatom increase does not always fit to a regular pattern. The observations made between 1950–55 are somewhat different from those made in the 1920–30 period; in later years the main diatom increase has sometimes been observed in May and some species, previously very common, have disappeared. Thus the radiolarian *Acanthonia* used to be an important component of the winter plankton; it is now rare. The more detailed year-round observations were made in the 1920–30 period, and have not been so intense since.

Changes in sea-water 'quality' appear to have taken place since 1952. Experimental hatchings of *Calanus* eggs and development of larvae proceeded normally up to about that year. Since then it has usually been necessary to add a chelating agent to the water to ensure normal development. Whatever may be the cause, it does not appear to have affected the *Calanus* stock in the Firth of Clyde as a whole. Less work appears to have been done on fish. Herring are perhaps the most important commercial fish in the Firth of Clyde, and their spawning grounds (Ballantrae Banks and Iron Rock ledges off S.W. Arran), and the spring breeding season, are well known. Some of the flatfish have also been studied. Other commercially important fish and shellfish require investigation, particularly with regard to their breeding times, and where and when the larvae are most abundant. The lobster, Norway lobster and scallop are probably the most important, although there is no major lobster fishery in the Firth of Clyde.

Flagellates and nanoplankton—Seasonal changes in nanoplankton organisms have received much less attention than those of diatoms and dinoflagellates. Early reports from Loch Striven indicated that adult *Calanus* was little dependent on flagellates, but since *Skeletonema* was too large in size as a food source for some zooplankton larvae, μ-flagellates could be of importance. Occasional references to flagellate populations are to be found in reports on oyster cultivation experiments at Millport. Using a total carbohydrate assay method it has been shown that a May 'bloom' of surface flagellates in Loch Striven caused an appreciable increase in carbohydrate values.

Studies on the physiology of microbial algae carried out by Droop and his associates have made major contributions to our knowledge of nanoplankton algae; numerous isolates used in these studies were obtained from the Firth of Clyde. However, the seasonal changes in nanoplankton organisms of the area have not been studied in any detail. Experimental studies on the growth kinetics, nutritional requirements, and adaptations to various ionic milieu, have all been subjects of investigation.

Living marine plankton consisting mainly of Calanus helgolandicus *with some* E. vadre nordmanni, *occurring in the Clyde Estuary* (*copyright photograph by Douglas P. Wilson, F.R.P.S.*).



Cultures of some flagellate organisms isolated from the Clyde Sea area have been used as food organisms in work on the nutritional requirements of *Calanus* and on subsequent egg production. Representatives of the Chlorophyceae, Euglenophyceae, Cryptophyceae, Chrysophyceae and Haptophyceae with type localities in the Clyde Sea area have been listed. Particular reference should also be made to papers on the Vitamin B_{12} requirements of certain organisms (Droop 1954, 1955, 1957, 1961, 1966, 1968 and 1970). The relevance of these laboratory studies to marine ecology has been stressed, in particular to aspects of growth kinetics such as 'luxury consumption' of certain nutrients and the relationship between concentrations of nutrient inside the cell and in the surrounding medium. The isolation of *Skeletonema costatum* in bacteria-free culture is of particular interest with regard to its frequent dominance in the annual spring outbursts in the Clyde Sea area. This organism was also shown to be dependent on exogenous sources of Vitamin B_{12}, and in further work on B_{12} uptake it was shown that growth of the organism in laboratory cultures (and presumably its rapid proliferation in the spring) could be limited by lack of Vitamin B_{12}. Specific growth rate (assuming that no other nutrient was limiting) was dependent on the concentration of the vitamin in the cells, not that in the surrounding medium. Relevant to this work is the interesting observation that *Skeletonema* cells carried too few epiphytic bacteria at the time of the spring increase for any nutritional or 'conditioning' factors to be operative, and that the number of bacteria/diatom cells remained constant throughout this time. Towards the end of the stationary phase, with increase in the numbers of moribund *Skeletonema* cells, there was also an appreciable increase in the attached saprophytic bacteria.

Comment—Much information is to be found in the literature, or is in the possession of individual workers, relevant to the breeding times of local populations of invertebrates and the periods when their planktonic larvae will be present in great abundance and hence most vulnerable to pollution (Table 1). There has never been a measure of primary productivity in the area using modern methods. Measurements in the sea lochs and in the open Firth at various times in the year would be worthwhile. It would also seem evident that whilst the general outlines of the seasonal phytoplankton changes have been known for many years, detailed quantitative studies over recent successive years are not available. Some spectulations are possible on the probable factors which 'trigger' the spring outgrowth. It may well be questioned whether more detailed quantitative studies will make any further major contribution to base-line data, since with few exceptions the spring outburst at least appears to be *Skeletonema* dominated. It is possible, however, that quantitative information on the seasonal changes in the subsidiary components of the phytoplankton flora may prove indicative of both short- and long-term environmental changes.

Occasional references are to be found in the literature to the μ-flagellate populations in the Clyde Sea area. This is one aspect which requires detailed study, since the pollutant-sensitivity of certain species has been demonstrated in laboratory experiments. A seasonal study of phytoplankton will be of little value unless accompanied by parallel investigations on relevant environmental factors (herbivorous zooplankton; nitrate, phosphate and silicate; salinity; temperature; light). A unified plan of operations would be necessary here to prevent needless duplication of effort.

Table 1 Literature relevant to local breeding times

Fish	Herring		Fishery Research Laboratory, Torry, Aberdeen
	Long rough dab and other flatfish	Dr. T. B. Bagenal	Freshwater Laboratory, Windermere
Ascidians		Dr. R. H. Millar	Dunstaffnage Lab., Oban
Crustacea	Decapods	Dr. R. M. Pike	Zoology Dept., Wellington Univ., New Zealand
	Euphausiids, Mysids	Dr. John Mauchline	Dunstaffnage Lab., Oban
	Cirripedes	Dr. Harold Barnes	Dunstaffnage Lab., Oban
	Copepods	Dr. S. Marshall	Universities Laboratory, Millport
Molluscs		Sir Maurice Yonge	13 Cumin Place, Edinburgh
		Dr. Alan Ansell	Dunstaffnage Lab., Oban
		Dr. Peter Barnett Mr. Clive Comely	Dunstaffnage Lab., Oban Dunstaffnage Lab., Oban (scallop)
		Dr. A. C. Stephen and Mr. R. E. Elmhirst	Publications in the Journal of the Royal Soc., Edinburgh and elsewhere.
Hydrozoa		Dr. C. E. Edwards	Dunstaffnage Lab., Oban

In an S.M.B.A., Annual Report, sometime in the late '20's or '30's, Mr. R. Elmhirst published an account of the breeding times of a number of the shore living organisms around Millport. This will be found useful.

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THE BENTHOS OF THE FIRTH OF CLYDE
AN ASSESSMENT OF THE PRESENT STATE OF KNOWLEDGE

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INTRODUCTION

The existence of the Millport Marine Station for over 70 years has lead to many publications on the benthos of the Firth of Clyde. A short appraisal prevents reference to most of this work and only that with importance in relation to future pollution studies is considered.

Comprehensive lists of species in the Clyde based on dredgings made as early as the mid-19th century. are given by Elliott, *et al.* (1901), King (1912) and Chumley (1918). More recently, since 1960, the Scottish Marine Biological Association has produced a series of publications listing the records of benthic species of various animal groups in the Clyde. At present, these groups are Polychaeta (Clark, 1960), Ascidiacea (Millar, 1960), Mollusca (Allen, 1962) Fishes (Bagenal, 1965), Crustacea: Euphausiacea and Decapoda (Allen, 1967) and Crustacea: Mysidacea (Mauchline, 1971). Nearly all these records are based on rather isolated and infrequent observations and do not take into account numerical abundance, except on a subjective basis, as for example, very common, scarce or rare. However, in 1955–56 the Department of Agriculture and Fisheries for Scotland (Aberdeen) made general quantitative benthic surveys in the Clyde fishing areas and although the results of this survey have not been published the data are available for reference (McIntyre, personal communication).

There is very little information on seasonal and long-term changes in the occurrence of recorded species or of their growth rates, and nearly all these records should be used with great caution in assessing future changes, other than dramatic ones. However the records do form a very useful basis for more detailed ecological work.

Most Clyde sediments are muds of varying types. Below 80m nearly all the bottom deposits are composed of fine mud inhabited by a *Nephrops—Calocaris—Brissopsis* community. In shallower waters the bottom is mainly of mixed muds, clays and sands with, in some areas, hard rock and stone. The intertidal zone is mainly rocky with some extensive areas of sand such as Hunterston Sands (Ayrshire) and Kilchattan Bay (Bute).

SAND BENTHOS

The intertidal sand of Kames Bay, Millport is probably one of the most intensively studied beaches in the world. General quantitative surveys of numerical abundance of animals on the beach were made by Stephen (1929) and Watkin (1942). Since 1960 student courses at the Millport Laboratory have made annual quantitative surveys of Kames Bay Beach in the spring and autumn. Most of these unpublished data are available. Stephen concentrated on the seasonal changes in the abundance and size of the bivalve *Tellina tenuis* (reviewed in Stephen, 1953). For one intertidal station in Kames Bay, he recorded the densities and size distribution of *T. tenuis* for the autumn of each year between 1926 and 1951. *Tellina* is clearly most important since it is one of the few benthic species for which information is available on long-term fluctuations in its ecology. Not only are there Stephen's Kames Bay records for 25 years but also those of the recent 12-year investigations into the effects of the Hunterston power station's heated effluent on the seasonal changes in densities and growth of *Tellina* (Barnett and Hardy, 1969; Barnett, 1971). Both these studies provide valuable baseline information against which to gauge any future changes. Information on *Tellina* shows that considerable fluctuations in densities can take place over long periods so that even the baseline data on numerical abundance varies considerably. Investigations of subtle effects on benthic populations will, therefore, have to be made over prolonged periods if subtle pollution effects are ever likely to be detected.

The ecology of the polychaete *Nereis diversicolor* (Smith 1953), cumaceans (Corey, 1970), harpacticoid copepods (Nicholls, 1935) and the growth and reproduction of the amphipod *Urothoe brevicornis* (Barnett and Hardy, 1969; Barnett, 1971), have also been studied in Kames Bay.

The shallow subtidal sand area of Kames Bay was surveyed in 1938–39 (Clarke and Milne, 1955) whilst Ansell *et al.* (1968) surveyed the same area in 1967 in more detail using aqualung diving techniques. Ansell (1961) has described in detail the biology of the common subtidal bivalve *Venus striatula* in Kames Bay. Clearly, the sand areas of Kames Bay have a useful future as a study area, particularly in view of the proposed industrialization of the Hunterston-Fairlie region.

The Hunterston area of the Ayrshire coast has been surveyed even more intensively; the thermal effects of the Hunterston generating station having been examined since 1964, and compared with the seasonal changes in the four years before the discharge of heated effluent (Barnett and Hardy, 1969; Barnett, 1970, 1971). A series of stations on an intertidal sandy beach and in the shallow subtidal area have been sampled regularly since 1960. The biology of the commonest benthic invertebrates is being described and will soon be published.

The Hunterston work will provide 12 years of data on seasonal changes in density and growth not only in *Tellina tenuis* but also in other molluscan, crustacean and polychaete species. It is hoped to continue this programme for at least another 5 years. The effects of the Hunterston power station have only been very slight, so that the present data should be useful for comparison with any future changes.

Other sandy intertidal areas in the Clyde have been examined by Stephen (reviewed in Stephen, 1953) who, again, paid particular attention to *Tellina tenuis*, and by McIntyre (1970) who described the age structure of recent *Tellina* populations from several beaches in South Ayrshire. Their results confirm those for *Tellina* at Hunterston and Kames Bay: that

great variations in year groups can take place, possibly as a result of much better spawnings in some years. Indeed, on some beaches entire year groups can be missing, indicating either total predation or mortality of newly settled spat, or the total absence of any settlement for that particular year. This certainly confirms the view that pollution effects on populations of benthic animals can be judged only against a long time series of observations. Elmhirst and Stephen (1929) observed that the bivalve *Spisula subtruncata* used to be extremely common on the sandy beaches of the Clyde and large numbers were taken for food and bait, but around 1890 the species died out in the Clyde for unknown reasons. Stephen (1938) reported some evidence of its re-establishment since 1932 although only isolated specimens have been found over the past ten years (personal observation). It is clear, therefore, that even under natural conditions very dramatic population changes of some benthic animals can occur, even to the extent of a common species virtually disappearing. Had such a disappearance of *Spisula* occurred in 1970 there would have been a strong tendency to look for some pollutant as the cause.

ROCKY AREAS

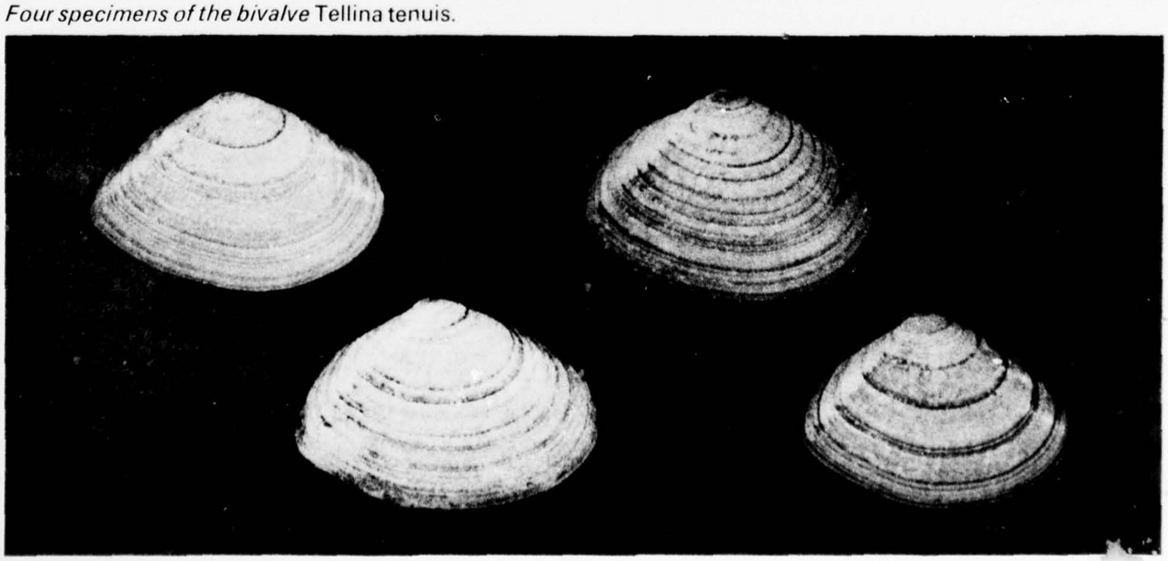
Rocky shores have a far greater abundance of species because they have a greater variety of microhabitats than sandy shores. Although the sandy shore lacks variety of species there is great abundance of those species which are present; it is also generally much simpler to take quantitative samples of sand, and the samples are usually more reliable statistically than those from the variable rocky habitat. These differences between rock and sand areas may account for the much larger amount of quantitative data available for the sandy regions in the Clyde.

The greatest amount of data is for rocky shores around the Isle of Cumbrae. The early Annual Reports of the Scottish Marine Biological Association give mainly descriptive accounts of the occurrences of species on various shores. Elmhirst (1923) has given some account of the breeding and growth of many rocky bottom species. More recent and more detailed information on a few species is available. Most significant is the work of Dr Barnes over the past 20 years on the biology of the Clyde cirrepedes (see the many papers in the Scottish Marine Biological Association Collected Reprints 1950–70) and of Barnes and Powell (1950, 1953) on the same group, although there is little information on seasonal fluctuations in abundance. Connell (1961a, 1961b), has described the interactions on the shore between the barnacle *Balanus balanoides* and its gastropod predator *Thais lapillus*. Other groups which have been investigated include the bivalve *Venerupis pullastra* (Quayle, 1949, 1952) and the common limpets *Patella vulgata* and *P. aspersa* (Davies, 1963).

Subtidal rock and stone areas have received very little attention in the Clyde, probably because of the difficulty in sampling, but recently aqualung diving has provided the means of sampling this area adequately. Millar (1952, 1954) has described the annual growth and reproductive cycles of some ascidians from this substratum.

In terms of assessing change on rocky areas of the Clyde, species records and subjective assessments of abundance at infrequent and isolated times are available. However, in contrast to the data available for some sand-dwelling species, no published long term data on numerical abundance and growth rates of any of these animals exist. This is unfortunate because rocky shores, with their exposed faunas, are likely to be affected more than sandy shores as for instance, during pollution by oil. However, the Biology Department of the University of Strathclyde (Dr E. J. Perkins, personal communication, and others) has recently been making quantitative assessments of rock and stone shore faunas of the Gare Loch and Loch Long with a view to determining

Four specimens of the bivalve Tellina tenuis.



changes over prolonged periods. This work is related particularly to the effects of oil pollution and oil pollution treatment effects (i.e. detergents) and also investigated effects of oil emulsifers on several rock and stone shore species, such as the dog whelk (*Thais lapillus*) and shore crab (*Carcinus maenas*).

MUD

Apart from many records from dredging surveys carried out over the past 100 years, which give comprehensive species lists for the Clyde muds, there is little information on the biology of mud-dwelling species. This is surprising because most of the bottom in the Clyde Sea Area is mud. Moore (1931) has examined the deeper muds of the Clyde, including some of the physical characteristics, whilst Lloyd (1931) has studied the mud bacteria. A more recent investigation is that of Allen (1953) on the epifauna of the deep muds, with particular attention to the scallop *Chlamys septemradiata*. The biology of only a very few mud species have been studied. For example, Bagenal (1952) has described the biology of the Norway lobster *Nephrops*, and Pike (1952, 1954) has described the growth and biology of two species of deeper water prawns. However, virtually nothing is known of long term changes or even of densities and growth of organisms in the Clyde muds and there is a great need for much more work on these topics. The Clyde River Purification Board (Mr D. Mackay, personal communication) is taking regular quantitative samples of the muddy bottom of the upper reaches of the Clyde estuary in an attempt to assess pollution effects on benthic species. The Board has a regular programme of Van Veen grab samplings from the area of the Garroch Head sludge dumping ground to assess the effects of sewage on the mud bottom fauna and has shown a change from a molluscan/echinoderm community outside the dumping ground to a polychaete community within the dumping area (Mackay *et al*., 1972). This change is typical of areas subjected to high levels of organic pollution.

For the past two years, the Aberdeen Laboratory, Department of Agriculture and Fisheries for Scotland, made benthic surveys on the Garroch Head grounds and used underwater television to show the dramatic decrease in the numbers and species of molluscs and other groups within the spoil ground area (McIntyre, personal communication).

The Garroch Head dumping ground is one of the few areas of the Clyde from which there are data on heavy metal concentrations. The Clyde River Purification Board has determined the concentrations of lead, copper, chromium, zinc, nickel, cadmium and manganese in the soft parts of *Crangon allmani, Pandalus montagui, Nucula sulcata, Chlamys septemradiata* and *Buccinum undatum* (Mackay *et al*., 1972). It was shown that animals from the spoil ground contained considerably larger concentrations of trace elements than animals from a control area 8 km distant.

CONCLUSIONS

The Clyde Sea is unusual in being one of the few estuaries for which we have a great deal of data on the benthos. Most of the data is descriptive and consists of invaluable lists of species, generally with subjective assessments of their abundance at infrequent intervals of time. Such information is valuable for future quantitative studies and may also be useful in assessing benthic community changes caused by pollution. However, Stephen's work on *Tellina tenuis* in Kames Bay and the present Hunterston Investigation of the Scottish Marine Biological Association are the only studies on the long-term quantitative changes in the benthos or long-term variations in growth of Clyde benthic species. Both these studies should, therefore, be extremely valuable in assessing changes caused by pollution in the Hunterston/Millport region and it is perhaps fortunate that these data exist for areas very close to the proposed industrial developments in the Hunterston/Fairlie region. However, these long-term field studies are of sand benthos and do not include either the rocky shores or the deeper muds, both of which are very important areas which are influenced by pollution. For both these areas there is little knowledge of biomass and none of seasonal and long-term fluctuations. For the benthos generally hardly any information exists on spawning and larval survival and growth, which are extremely important in the maintenance of benthic communities.

Until the very recent results of the Clyde River Purification Board study (Mackay *et al*., 1972) of the Garroch Head dumping ground there was no published information on the accumulation of pollutants like heavy metals and organochlorides in the Clyde benthos. The Department of Agriculture and Fisheries for Scotland have made organochloride analyses on Clyde fish but similar studies on the benthos are needed. Meanwhile, the Department's Aberdeen Laboratory is surveying heavy metal concentrations in the benthos of Irvine Bay (McIntyre, personal communication).

The surveys of the Department of Agriculture and Fisheries for Scotland and the Clyde River Purification Board are thus making an important contribution to knowledge of heavy metal concentrations in the Clyde benthos and sediments. It is to be hoped that these studies will be continued and that similar surveys will be undertaken for an even wider range of benthic communities.

BENTHOS OF THE FIRTH OF CLYDE

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FLORA AND FAUNA OF THE CLYDE ESTUARY

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INTRODUCTION

The Clyde sea area can be divided into three parts, the firth, the sea lochs and the estuary. The last of these is shown by Chumley (1918) as extending eastwards from a line drawn between Gourock Pier and Kilcreggan Pier, and excluding the Gare Loch north of a line between Roseneath and Rhu. The area referred to here corresponds to this definition and extends eastwards as far as the tidal weir.

The flora and fauna of the estuary, as defined above, have been less studied than those of the firth or the sea lochs. Chumley did not include it in his survey, and no local records of substance can be found. This lack of information is unfortunate since the upper estuary although now severely polluted, exhibits features of great interest in both flora and fauna.

The Biology Department at Paisley College of Technology has recently studied some biological aspects of the estuary, and this report is concerned with these studies; the observations are exploratory, and so far confined almost entirely to the littoral region, although an extension to the sub-littoral is planned in collaboration with the Clyde River Purification Board.

DESCRIPTION OF THE ESTUARY

The estuary may be further sub-divided as follows:

The narrow upper portion, which is largely canalized, terminating to the west of Erskine: the water is grossly polluted and both flora and fauna severely restricted.

Wide banks of tidal mud and sand, varying somewhat in composition, stretching to Port Glasgow on the south side and to Helensburgh on the north: patches of *Zostera* occur, as well as algae, and the most notable feature of the fauna is perhaps the large winter flocks of birds.

Stony and rocky shores extending westwards from Port Glasgow to Lunderston Bay, beyond Cloch Point in the firth, interspersed by the shipyards, docks and harbour-works of Port Glasgow, Greenock and Gourock; on the north side boulders and rocky outcrops, especially on the upper shore, become more numerous towards Ardmore Point, and again at Helensburgh. The shore at Kilcreggan is also rocky.

THE INTERTIDAL BENTHIC ALGAE OF THE ESTUARY

Table I summarises the results of preliminary surveys of the attached algae undertaken by Dr. Martin Wilkinson in Spring and Summer 1972. As some taxonomically difficult species were encountered the totals cannot yet be regarded as firm. There are difficulties in interpreting the figures in Table I because of variation in nature of the substrate between different sites. In general, however, going upstream, there is a reduction in the number of species, with red algae being eliminated first, brown algae being very reduced in number, and the appearance under less saline conditions of Xanthophyceae represented by *Vaucheria* sp. The numbers of species at all sites in the estuary is lower than at many sites in the firth, of which Wemyss Bay is quoted as an example (Table I).

Since shelled animals were not found at Erskine, Langbank, Dumbarton, Braehead, Partick and Glasgow Green, the totals for green and blue-green algae at these sites are slightly lower, owing to the absence of shell-boring species.

Diatoms were not counted in the survey but mention must be made of *Melosira nummuloides* which was the dominant organism on the lower shore at Braehead and Erskine where it formed a brown turf.

Table I - Numbers of Species of Attached Algae

SITE	Distance downstream of Tidal Weir (km)	Chlorophyta	Phaeophyta	Rhodophyta	Cyanophyta	Xanthophyceae	Total
FIRTH							
Wemyss Bay	—	8(12)	7(6)	19(16)	2(2)	0(0)	37(36)
ESTUARY-SOUTH BANK							
Gourock (Ashton)	41	10(14)	9(11)	8(11)	2(2)	0(0)	29(38)
Greenock (Esplanade)	37	10(8)	3(4)	3(9)	2(2)	0(0)	18(23)
Parklea	26	8(10)	5(5)	2(4)	2(2)	0(0)	18(21)
Langbank (West Ferry)	22	–(6)	–(4)	–(0)	–(0)	–(0)	–(10)
Longhaugh Lodge	18	–(5)	–(3)	–(0)	–(0)	–(1)	–(8)
Erskine	15	8(5)	1(1)	0(0)	0(0)	1(1)	10(7)
Braehead	7	5(7)	1(0)	0(0)	0(0)	1(1)	6(8)
ESTUARY-NORTH BANK							
Craigendoran (W. of Pier)	34	9(8)	4(10)	7(8)	2(2)	0(0)	22(28)
Ardmore Bay	31	–(10)	–(6)	–(9)	–(2)	–(0)	–(27)
Cardross	27	9(10)	5(8)	3(5)	2(0)	0(0)	18(23)
Ardoch	25	–(12)	–(5)	–(5)	–(2)	–(0)	–(24)
Dumbarton Castle	22	8(6)	3(1)	1(0)	0(0)	0(0)	12(9)
Partick (W. of Kelvin mouth)	4	–(7)	–(0)	–(0)	–(2)	–(1)	–(10)
Glasgow Green (just below tidal weir)	0	–(4)	–(0)	–(0)	–(1)	–(1)	–(6)

Unbracketed figures refer to Feb/Mar 1972. Bracketed figures refer to July 1972.
0 none present in sample. – no sample taken.

The distribution of algae, in general terms, does not vary from that which might be expected in an estuary. It would seem difficult to interpret the distributions in terms of specific factors such as various pollutants since it is possible that salinity changes play an overriding role in determining the distribution pattern.

FAUNA OF ROCKY SHORES

No complete surveys of rocky shore animals have been made so far. A small number of common animals whose distribution is moderately predictable have been recorded on the south side of the estuary.

The figures in table 2 represent scores as follows:

4 – Abundant; dominant in suitable situations
3 – Common; visible in suitable places at a glance
2 – Scattered; some searching needed
1 – Occasional; only one or two seen, possibly casual
0 – Absent

Table 2	Gourock (Bay)	Greenock (Esplanade)
Halichondria panicea	2	2
Actinia equina	3	1
Tubificids	2	3
Mat-forming worms	2	3
Pomatoceros triqueter	2	1
Balanus balanoides	4	4
Patella vulgata	3	3
Littorina littorea	4	4
Thais lapillus	3	3
Buccinum undatum	2	2
Mytilus edulis	4	4

Table 2 (cont.)	Newark Castle	Port Glasgow (East)	Erskine
Halichondria panicea	0	0	0
Actinia equina	0	0	0
Tubificids	3	2	4
Mat-forming worms	4	4	0
Pomatoceros triqueter	0	0	0
Balanus balanoides	4	4	0
Patella vulgata	0	0	0
Littorina littorea	3	3	0
Thais lapillus	0	0	0
Buccinum undatum	0	0	0
Mytilus edulis	4	3	0

Mat formations are one of the most notable features of the more polluted shores. Travelling from east to west, they are first conspicuous on the stakes of the timber ponds east of Port Glasgow and are a dominant if variable feature as far as the west of Greenock. On this stretch of shore the mat consists largely of the tubes of *Fabricia sabella*, with a few *Pygospio elegans* in places. Associated organisms include *Jaera albifrons*, harpacticoids, tubificids and turbellarians, with some colonial ciliates.

West of Princes Pier the variety of the shore fauna generally increases and mat formation becomes restricted. *Polydora ciliata* becomes conspicuous as a mat builder and is dominant at Gourock, at least on the lower shore. *Fabricia sabella* again occurs in large numbers west of Gourock in the algal turf referred to above, to which it contributes a large content of silt and mud. The dominant algal component is *Rhodochorton* and in the associated fauna *Tanais cavolini* is conspicuous.

On the north side of the estuary rocky shores are fewer. West of Cardross, at Ardmore Point, and also at Kilcreggan the fauna includes the common species that might be expected. At Helensburgh irregular distribution of some animals might be related to pollution, and some patches of mat occur in which both *Fabricia sabella* and *Pygospio elegans* are numerous, along with several associated species.

Hunter and Hunter (1963) published a note on the distribution of *Buccinum undatum* in this area, which they found at Ardmore Point and eastwards almost to Cardross. They found dwarf individuals associated with the littoral habitat and pointed out that the penetration of the species into the estuary corresponded exactly with that of *Asterias rubens*, a species intolerant of brackish conditions.

It is difficult to separate the effects on animal distribution of the various factors which might be involved, particularly salinity. There are, however, points of resemblance between both the fauna and algae of these shores and shores in the Firth of Forth and elsewhere which share similar levels and types of pollution (Smyth, 1968; O'Sullivan, 1971). Both the Port Glasgow/Greenock areas are heavily polluted. Like the algae, the fauna is nowhere so varied as on comparable shores at Largs, Portencross or Cumbrae.

Rocks with Mytilus *and* Fabricia *mat, Newark Castle.*

FAUNA OF THE MUD FLATS

The birds are the best studied feature of the mud flat fauna. Regular counts have been made in parts of the area by the British Trust for Ornithology.

Table 3

Representative counts of birds on the Clyde estuary (supplied by E. T. Idle of the Nature Conservancy).

	Langbank/Erskine		Ardmore/Rhu	
	15.2.71	14.3.71	17.1.71	20.2.71
Cormorant	36	71	—	4
Mallard	(200)	50	2	(74)
Pintail	4	37	—	—
Goldeneye	286	105	1	60
Scaup	170	2	—	—
Eider	—	—	(400)	(600)
Shelduck	588	350	90	43
Oyster-catcher	(1500)	1254	200	(350)
Lapwing	(1000)	(400)	25	(325)
Curlew	20	10	(100)	58
Redshank	(3600)	(3500)	40	53
Knot	108	12	—	—
Dunlin	(2800)	(700)	—	1

Other birds recorded including very large numbers of gulls are not given.

The figures indicate some of the largest concentrations of shore birds in the country, and a winter feeding-ground of considerable importance.

Two local ornithologists have been studying movements of the more important flocks and relating them to time of day and tidal exposure. This has shown some selection of feeding grounds and studies are now being made to relate this to variations in the distribution of food organisms.

The size of the bird population indicates the presence of a substantial biomass of aquatic animals as a food supply. In 1962 Hunter and Hunter published a survey of the *Hydrobia ulvae* population on the north side of the estuary from Ardmore to near Ardoch, and including the Pillar Bank. Their data showed two density levels averaging 5,443 and 7,954 animals per m ^{2} respectively, but in places the population reached densities of 10,000, 20,000 and, exceptionally, 40,000 per m ^{2}. Their rough estimate of the total population in the area was 3×10^{10} individuals.

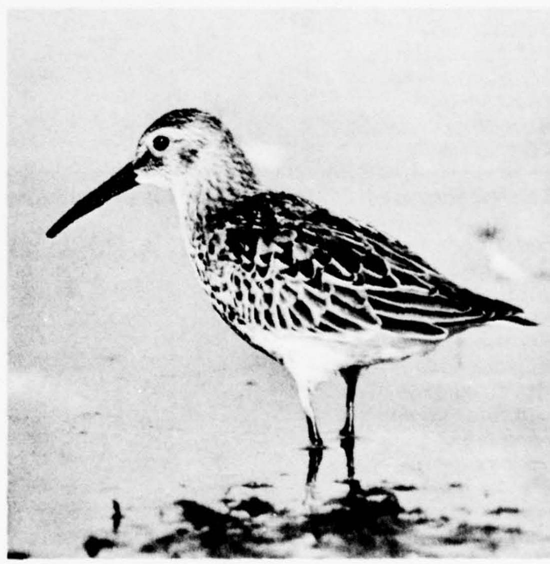
Other components of the mud flat fauna which have been studied include *Nereis diversicolor* in an area on the south side between Erskine and Langbank. Between December 1969 and March 1970 fairly uniform numbers were found with a mean of 860 worms per m ^{2}, individual samples lying between 80 and 1650 per m ^{2}. Variations in numbers and biomass were correlated with several physical and chemical features of the habitat.

Other members of the fauna include *Macoma baltica, Corophium* and *Arenicola,* together with beds of *Mytilus edulis*. The Clyde River Purification Board has taken some samples in the area, and reported in 1969 an extension of the range of *Macoma* upstream from the 13-mile (21 km) to the 11-mile (17.5 km) station (measured from the tidal weir) and of *Nereis* from the 11-mile (17.5 km) to the 10-mile (16 km) station.

FUTURE STUDIES

The Clyde River Purification Board has already carried out preliminary sampling of the sub-littoral benthic fauna and the Paisley College is collaborating in extending and developing these studies. A study has commenced of the accumulation of break-down products of insecticides by algae, the distribution of insecticides in the waters and the benthic algae of the Clyde.

A dunlin (photo by courtesy of Eric Hosking).



FLORA AND FAUNA OF THE CLYDE

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A REVIEW OF STUDIES ON THE SEAWEEDS OF THE CLYDE SEA AREA

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THE SPECIES PRESENT AND THEIR DISTRIBUTION

During the latter half of the 19th century few regions were more intensively searched for marine algae than the Clyde sea area. The unpublished records of Balfour, Hennedy and Robertson were assembled by Batters (1901) and listed together with his own collections. The region has a rich mixture of northern and southern forms and Batters (1901) estimated that of the seaweed species then known from the British Isles more than half occurred in the Clyde sea area.

No witnessed collecting on a comparable scale has been done since. The more comprehensive of the 20th century lists are those of Gibb (1939), Krinos (1969) and McAllister *et al.* (1967). In addition, in recent years Norton (unpublished) has collected frequently in a few of Batters (1901) sites.

It was hoped that comparing old and recent records for various sites might show changes in the composition of the flora in the last 70 years, but, except for the Isle of Cumbrae, every site that has been re-investigated now has more species than those recorded by Batters (1901). However, this does not indicate that the vegetation at these sites is now more diverse because the earlier collections may have been incomplete, and it is clear that at some sites only a few algae were collected. However, at Cumbrae, Batters' list must be comprehensive and the 278 species recorded is large for any shore in the British Isles. Recent collections (Norton unpublished) have revealed only 122 species at the same site, but more collections are being made to ensure that the recent list is as near definitive as possible. The records by Batters (1901) and by Norton (unpublished) are compared in Table 1.

Table 1

A comparison of the number of seaweeds recorded by Batters (1901) and Norton (unpublished) for various sites in the Clyde sea area.

	1901	1971
South-east Cumbrae, Bute		
Chlorophyceae	51	19
Phaeophyceae	89	37
Rhodophyceae	116	66
Cyanophyceae	22	not collected
totals	278	122
Portencross – Seamill, Ayrshire		
Chlorophyceae	10	19
Phaeophyceae	19	37
Rhodophyceae	26	69
Cyanophyceae	1	4
totals	56	129
Denure – Heads of Ayr, Ayrshire		
Chlorophyceae	3	9
Phaeophyceae	8	31
Rhodophyceae	13	50
totals	24	90

The records for Cumbrae suggest that species diversity has greatly reduced in this century. However, the reduction may not be as dramatic as it appears for several reasons:-

Firstly, some of the early records are undoubtedly based on misidentifications. The specimens in the herbaria of Batters, Robertson and other early collectors are at present being checked in order to authenticate their records.

Secondly, at least some of the older records may have been based on plants cast up on the shore. The strand line was a favourite collecting ground for it was a convenient source of plants normally found in the sublittoral zone. Such plants may not occur in the collecting locality, but may have drifted from neighbouring shores many miles away.

Thirdly, many entities to which early collectors gave names are now considered almost impossible to differentiate. For example, few species in genera such as *Cladophora, Monostroma, Callithamnion, Ceramium, Gelidium* and the calcareous encrusting Corallinaceae can be determined with any confidence. Batters (1901) records for Cumbrae no less than 39 species from these genera alone.

Finally, the list compiled by Batters (1901) was the result of years of collecting on Cumbrae by phycologists specifically looking for rarities and it is being compared with recent collections made over a relatively short period of time.

A few of the sites mentioned by Batters (1901) are close to the mouth of the river Clyde e.g. Gourock. As these sites are most likely to have been affected by industrial development they are being examined by the author to see if the same species of seaweed are still present.

However, even if the same species diversity is found it does not show possible changes in the abundance of individual species. In an early paper Batters (1891) gives subjective estimates of abundance of some species in the region and all of the species that he describes as common would be considered so today.

Several species of seaweeds have flourished in the Clyde sea area since late glacial times as excavations at Greenock and Renfrew have shown (Robertson, 1881; Brett and Norton, 1969). Such fossil remains of non-calcareous algae are extremely rare.

TAXONOMIC AND LIFE HISTORY STUDIES

Rhodophyceae—Conway (1964a) reviewed the genus *Porphyra* with material gathered from Cumbrae and Farland Head, Ayrshire.

In other papers Conway describes the reproduction and life histories in culture of *Porphyra leucosticta* (Conway, 1963), *P. umbilicalis* (Conway, 1964b) and *P. miniata* (Conway, 1967).

Using material collected in Ardneil Bay, Ayrshire, Knaggs and Conway (1964) described the production of spores and early development of *Rhodochorton floridulum* in culture. Other aspects of the taxonomy, morphology and cytology of *R. floridulum* and *R. purpureum* are described by Knaggs (1963).

ECOLOGICAL STUDIES

Surprisingly little ecological work has been done on the seaweeds of the region. Lewis and Powell (1960) briefly described some aspects of the zonation on the east coast of Kintyre and in Loch Fyne. Gibb (1939) described the intertidal communities on the north of Great Cumbrae in detail and gave subjective estimates of the abundance of each species.

A few accounts have been published of the distribution of sublittoral algae in the region. Kain (1961) dived in 3 sites off the Cumbraes. Diving surveys were also carried out for two sites in Ayrshire by McAllister *et al.* (1967) and further discussed by Conway (1967). Norton and Milburn (1972) described the underwater associations in the Kyles of Bute and at the mouth of Loch Riddon. The latter two papers both emphasised the importance of the herbivorous brittle-star *Ophiocomina nigra* in controlling the distribution of sublittoral seaweeds.

Observations were made of the colonization of treated and untreated panels on floating rafts which were moored off Keppel pier for tests of anti-fouling compounds, Elmhirst (1944). Regardless of the time of year, newly submerged untreated surfaces were first colonised by diatoms followed rapidly by filamentous green algae such as *Ulothrix* and *Urospora* and subsequently by *Enteromorpha, Ulva, Cladophora* and *Ectocarpus*. The latter often predominated especially in more exposed sites. A wide variety of algae infested the rafts during the summer. In autumn the amount of algae present decreased markedly and many species became infested with diatoms. Throughout the autumn and winter further settlement of spores enabled *Laminaria, Desmarestia* and *Petalonia fascia* to dominate the vegetation early in the following year. In March the amount of algae on the rafts greatly increased. This was found to result from the growth and regeneration of existing plants rather than the development of newly settled spores.

A similar sequence of colonization was found in denuded and sterilized areas of the shore in the vicinity of Keppel pier, Elmhirst (1949). A primary settlement of diatoms in the spring was followed by a prolonged phase of dominance by fast growing annuals (often Chlorophyceae) during the summer and autumn. Beneath this protective cover the sporelings of the slower growing perennial brown and red algae were able to develop and subsequently dominate the area. The length of time that each of these phases persisted depended upon the time of year at which the area was cleared, the climatic conditions and, to a lesser extent upon the intensity of competition with sedentary animals. Many algal species were able to begin development well above their normal well-defined zones only to perish when the sporelings out-grew the protective layer of vegetation covering the rock. Powell (1950) noted the very high mortality of some species, for example a quadrat cleared in May bore over 14,000 buttons of *Himanthalia elongata* by the spring. Thousands were subsequently crowded out as the diameter of each increased and many of those remaining a year later were very elongated and precariously attached as a result of crowding. High mortality was also observed in very dense populations of *Fucus serratus*.

Conway (1942) gives a brief account of the utilization of the seaweeds of the region by man.

Phaeophyceae—Gibb (1957) studied the development, rate of growth and ecology of the unattached forms of one of the commonest seaweeds in the Clyde sea area, *Ascophyllum nodosum*. Some of her data were gathered from plants growing on mud in Loch Riddon, Argyll. The plant normally forms long stringy thalli attached to rock, but in L. Riddon (and also L. Rhanza in Arran) the ecad called *'mackii'* forms loose-lying globular tufts 15 cm or so in diameter.

Gibb (1957) showed that the thalli of the loose-lying plants extended at only $\frac{1}{2}$-$\frac{1}{3}$ the rate of the attached plants. Also, in contrast to the attached plants, they often lack air bladders, are yellow not olive green, branch dichotomously not monopodially and become fertile apically as well as laterally. Gibb (1957) attempted to explain these variations in terms of differences in salinity, light and substrate.

Kain (1962) described the vertical distribution of the dominant sublittoral seaweeds off the Cumbraes and the Isle of Bute, in relation to nature of substratum and angle of slope. She found that *Laminaria saccharina* was dominant at each site and at all depths except near the top of a profile at the most exposed locality examined, where *L. hyperborea* was most abundant. Moreover, where both species occurred together their lower limits were the same. She concluded that light was unlikely to be the factor enabling *L. saccharina* to predominate, but that shelter from wave action might be.

Kain (1963) described the age, weight and length of plants of *L. hyperborea* collected from a depth of 2 m at Gull Point, Little Cumbrae. Here the age peak of the plants was 3-4 years and the oldest plants were 8 years old. The stipes (the perennial part of the plant) weighed significantly less than those of plants of the same age collected elsewhere in Britain.

The laminarian algae of the region were also extensively sampled by the Institute of Seaweed Research when investigating their possible exploitation. Samples were taken using a large spring grab from east and south-east Kintyre (Walker, 1950; Richardson, 1954) and around Ailsa Craig, Inchmarnock and Arran (Walker, 1950, 1958; Walker and Richardson, 1957). At all these sites there was a progressive decrease in the standing crop of *Laminaria* with increasing depth; about 90% of the total crop occurred in relatively shallow water, 0-9 m below MLWS (Walker and Richardson, 1957).

At east and south-east Kintyre laminarians were present from 0-9 m at a mean density of 32.7 tons (fresh weight) per hectare. *L. hyperborea* was dominant in all but the deepest samples where *L. saccharina* was more abundant. Both weight and percentage cover decreased progressively with increasing depth (Walker, 1950; Richardson, 1954). The results of this work are summarized in Tables 2, 3 and 4. The most significant facts to emerge from the surveys were that:—

There was a substantial increase in both the fresh weight and percentage cover of algae in summer (Table 2) as new plants arose and existing plants produced new laminae.

There were some variations in the composition of the flora in consecutive years. For example, in 1949, of the samples taken in 1-11 m off south west Arran only 19% (by fresh weight) of the plants found were *L. hyperborea*, 37% were *L. digitata* and 44% were *L. saccharina*. However, samples taken in the same area, at the same depths and the same time of year in 1951 contained 86% *L. hyperborea*, no *L. digitata* and only 13% *L. saccharina* (Walker, 1952). Smaller fluctuations were noted in other years by Walker (1953, 1957) and Walker and Richardson (1957). However, in most years *L. saccharina* was dominant except in shallow water and often formed an almost pure stand from 7-16 m below MLWS (Walker, 1953; Walker and Richardson, 1957).

There was a marked decline in density (weight/unit area) from 1949 to 1953-4. There was then a progressive recovery from 1954 to 1956 (Table 3 and 4). This decline and recovery were recorded at each site sampled and were similar to a general pattern of fluctuations recorded elsewhere on the coasts of Scotland at that time (Walker and Richardson, 1957).

From these and other similar surveys carried out elsewhere on the Scottish coast Walker (1954) concluded that:

The fresh weight of Laminariaceae was proportional to their percentage cover.

The reduction in their density with increasing depth followed an exponential scale. This he related to the co-efficient of extinction of visible light which is also logarithmic through water.

Rhodophycaea—During the second world war the supplies of agar – agar from Japan ceased and the government instigated various projects to assess the possibility of extracting agar substitutes from native seaweeds. The studies became concentrated on two species, *Gigartina stellata* and *Chondrus crispus* and some of the work was done in the Clyde sea area.

C. crispus was present at a few sites in the region, but not in harvestable quantity. *G. stellata* on the other hand, formed a wide belt over the whole of the lower exposed shores, especially on south-facing exposed shores. Newton (1949) gives a great deal of quantitative data on the standing crop of *G. stellata* for the whole of the region and records quantities of up to 1.5kg/m^2.

Much of the work on the development and seasonal behaviour of the plants was carried out on Cumbrae. Vegetative growth began in May and standing crop reached a maximum in July, decreasing throughout the autumn and winter as plants were removed by gales. Experiments indicated that it was advisable to take only a single harvest per year and that harvesting in July gave the best yield (Newton, 1949). It was also found that hand picked plots recovered better than those on which the plants had been cut with shears. It was suggested that this was because in hand picked areas many plants were left behind and these protected the germinating spores and young plants developing beneath. The failure to produce plants from spores settled in culture on perspex slides which were then transplanted onto the shore was

Table 2

Seasonal fluctuations in the quantity of *Laminaria* off northern Arran (Walker, 1953) 0–9m. – total area 174 hectares.

	Total Fresh wt. tons	Density tons/hectare	% cover
Feb.–Mar. 1953	1505	8.6	43
May–June 1953	3526	20.3	64
9–18m – total area 259 hectares			
Feb.–Mar. 1953	384	1.5	14
May–June 1953	1792	6.9	38

Table 3

Annual fluctuations in the quantity of *Laminaria* off south west Arran, total area 1,072 hectares (Walker, 1952)

	Total Fresh wt. tons	Density tons/hectare	% cover
Sept.–Nov. 1949	123,200	114.8	99
Sept.–Nov. 1951	33,900	31.6	59

Table 4

Annual fluctuations in the quantity of *Laminaria* off the northern half of Arran, total area 733 hectares (calculated from Walker and Richardson, 1957 and Walker, 1957).

	Total Fresh Wt. tons	Density tons/hectare	% cover
Jan.–Feb. 1952	8,465	11.6	32
Jan.–Feb. 1953	5,329	7.2	41
Jan.–Feb. 1954	4,081	5.4	42
Jan.–Feb. 1955	6,484	8.9	53
Jan.–Feb. 1956	10,023	13.5	62

Density = fresh wt. of *Laminaria* per unit area.
Cover = the number of quadrats which contained *Laminaria* expressed as a percentage of all quadrats.

also attributable to the lack of a protective covering of other plants (Newton, 1949). If the rock itself was cleared, sterilized and then 'seeded' with spores of *G. stellata* in October, the area was first recolonized by *Enteromorpha linza, Porphyra umbilicalis* and a little *Petalonia fascia* before *G. stellata* reappeared. Powell (1950) found that *G. stellata* took considerably longer to reappear on areas that had been scraped and then sterilized with a flame gun than on areas which had only been scraped. He concluded that scraping alone does not completely remove the tenacious encrusting system of *G. stellata*.

Powell also settled carpospores on sterilized sandstone blocks in culture then secured them in carriers fixed in the *Gigartina* zone on the shore at Keppel. The blocks were put out in the field in November but remained bare until mid-January when they became infested with diatoms. By March these had been replaced by a variety of algae and in early April the initial basal discs of *G. stellata* became apparent. These discs had expanded and coalesced into sheets by June and minute erect fronds began to arise from them. In spite of the feeding by the herbivorous snail *Littorina littoralis*, after 18 months a block of only 1290 mm^2 bore 224 fronds of *G. stellata* some over 14 mm tall.

In culture a similar life history was demonstrated, i.e. the development from carpospores of a plant similar to the parent from which the spores were derived (Elmhirst, 1949).

At the upper limits of its zone, attempts were made to increase the standing crop of *G. stellata* by weeding out competing species. Plots weeded in June were at first recolonised by *Enteromorpha compressa* and *Ulva lactuca* which was gradually replaced by *G. stellata*, but by the following June the plot did not support a larger standing crop than the unweeded control areas (Newton, 1949).

Conway (1946) observed that grazing by the limpet *Patella vulgata* reduced the cover of *G. stellata* on Cumbrae.

Knaggs (1963) studied *Rhodochorton floridulum* at Ardneil Bay, Ayrshire where it forms an extensive carpet on sandy boulders throughout most of the littoral zone, and is often covered by several inches of sand during low tide. Knaggs (1963) showed that there was no marked difference in the percentage of apices actively dividing at different levels on the shore or in the same plant at different times of day.

Cyanophyceae—Stewart (1961) isolated three species of blue-green algae from the supralittoral fringe at Portencross and West Kilbride, Ayrshire. He showed that the commonest species *Calothrix scopulorum* was able to fix atmospheric nitrogen, a capability which may be of great ecological significance in a habitat where there is probably a shortage of nitrogen.

He also found that in culture *C. scopulorum, Nostoc entophytum* and *Oscillatoria brevis* were tolerant to a wide range of salinity as might be expected in organisms inhabiting the supralittoral fringe. All three species showed optimal growth at a salinity of between 7 and 13‰. The species tolerated a range of pH from 5.6-10.2 with optima at 8-9, but Stewart (1961) concluded that this was unlikely to affect the distribution of these algae.

CHEMICAL AND PHYSIOLOGICAL STUDIES

Phaeophyceae—Knights (1970) extracted fucosterol plus traces of C_{27} and C_{28} sterol from *Ascophyllum nodosum* collected in the Gare Loch. If the plants were exposed to air for four weeks further sterols appeared, probably as the result of the aerial oxidation of fucosterol.

Black (1954) analysed the chemical composition of a single plant of *Laminaria saccharina*. The plant was collected from Shandon in the Gare Loch in August, during the period of slow-growth, and showed considerable variations in composition along the length of the lamina in tissues of different ages. The concentration of laminarin was low in the vicinity of the transition-zone meristem, but increased along the lamina reaching a maximum approximately two-thirds of the distance to the tip, the distal tissue having spored or been severely eroded. Iodine and fucosterol were concentrated in the transition-zone where they are in all probability required for new growth.

The Radiobiological laboratory of the Ministry of Agriculture, Fisheries and Food make routine analyses of the radioactivity in *Fucus spiralis* from the vicinity of the nuclear power station at Hunterston, Ayrshire. The discharges rose during 1969, the latest year for which figures are available (Table 5). In addition to caesium-137, traces of zinc-65 were detected in the seaweed as well as occasional traces of Windscale-derived fission products. Concentrations were low and of no radiological significance, *F. spiralis* serving merely as indicator material.

Rhodophyceae—Water soluble polysaccharides were extracted from *Porphyra leucosticta, P. purpureum* and *P. umbilicalis* collected from various

Table 5

Radioactivity in materials in the vicinity of Hunterston 1969 (modified from Mitchell, 1971).

	Concentration of radioactivity – mean and range			
	Total betacounts	^{65}Zn	^{106}Ru	^{137}Cs
Seawater	—	—	—	3.8
(pCi/litre)				(2.4–6.6)
Sand	14	—	—	0.7
(pCi/g dry wt.)	(9.3–19)			(0.1–2.4)
Fucus spiralis	7.8	0.1	0.3	1.4
(pCi/g wet wt.)	(4.4–10)	(0.08–0.2)	(0–1.1)	(0.4–3.1)

sites in the region by Rees and Conway (1962). Several polysaccharides were isolated and their structure determined. A wide variation in the proportion of individual polysaccharides was found. An attempt was made to correlate these variations with season of the year and the level on the shore at which the plants were found (Rees and Conway, 1962).

Newton (1949) reports that of the seaweeds collected in the region *Gelidium corneum* yielded only 20% of its dry weight as agar whereas 50% of the dry weight of *Gigartina stellata* was an extract which formed a soft and viscous gel. The report also contains considerable data on the properties of the gel and the effects on the extract of storing the plants under different conditions.

Cyanophyceae—Stewart (1961) demonstrated nitrogen fixation in *Calothrix scropulosum* and *Nostoc entophytum,* but not in *Oscillatoria brevis.* All three species were collected from the Ayrshire coast. Both nitrogen fixing species were found to exude in culture reducing sugars, polysaccharides and fixed nitrogen. The exuded nitrogen was mostly in the form of amino acid nitrogen and the amounts exuded varied with the stage of growth of the algae.

Amino acid analyses showed no marked differences between the nitrogen fixing and the non-nitrogen fixing species. All the common amino acids were detected in the form of $\alpha \lesssim$ – diaminopimelic acid, citrulline, ornithine and undetermined ninhydrin positive substances (Stewart, 1961).

CONCLUSIONS

This review shows that in spite of the large amount of work done there are several gaps in our knowledge of the seaweeds of the Clyde sea area, these are:

The reasons why seaweeds occur where they do. Very little is known of the response of seaweeds to factors such as reduced salinity, exposure to or shelter from wave action, turbidity and sedimentation, grazing, competition with other seaweeds or with sedentary animals, and the variety of substances resulting from man's activities. Some of these factors could be investigated through culture experiements in the laboratory and transplants in the sea.

There is almost no quantitative information on the seasonal fluctutations in the abundance of seaweeds or on the changes in seaweed populations from year to year. Such data are needed if we are to measure acute changes supposedly resulting from man's activities. Work to make good this deficiency is planned.

Changes which may have occurred over a much longer period of time in the past could be determined by a more detailed and critical comparison between the early records of Batters (1901) and the present day flora of Cumbrae. If, as seems likely, a reduction in the number of species present is found (Table 1), it should be possible, by means of the laboratory experiments suggested above, to determine whether the missing species are those most susceptible to factors in the environment which are more prevalent today than they were before the turn of the century. Any changes in the quantities of the commoner species could be investigated by re-surveying the seaweed communities of Cumbrae that were examined by Gibb (1939).

Finally, few analyses have been carried out to determine the concentration of any substances in seaweeds. As some species are found growing close to sewage outfalls and may accumulate some pollutants they might act as useful indicator species.

Typical zonation of seaweeds on a moderately sheltered shore, Down Craig, Isle of Cumbrae. Below the distinct band of Venucaria, *amidst the barnacles are small scattered plants of* Pelvetia canaliculata *and* Fucus spiralis, *a runnel of* Enteromorpha intestinalis (*left*) *and the bladdered straps of* Ascophyllum nodosum (*foreground*).

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A NOTE ON FISHERIES IN THE CLYDE

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Details of catches of the Clyde fisheries are published annually in the Department of Agriculture and Fisheries for Scotland's Sea Fisheries Statistical Tables. Accounts of research are given each year in the Marine Laboratory's Annual Reports, the Scottish Fisheries Bulletin and in a number of scientific publications, including those of the International Council for the Exploration of the Sea. Details of these, together with some additional relevant references are listed at the end of this note.

The main demersal fisheries in the Clyde sea area are carried on by small boats, seine-netters and light trawlers, landing chiefly at Ayr and Campbeltown. The mean annual weight landed over the past 10 years was 5,239 tons with a value of £483,033. The bulk of these demersal landings were made up of 6 species; cod, whiting, haddock, hake, saithe and plaice.

For statistical purposes, it is convenient to divide the Clyde into an upper section, north of 55½°N, and a lower section, south of this line. Table 1 shows the annual landings of the six main species, and also the total demersal landings for the two areas since 1961. The fluctuations in saithe landings probably reflect changes in market demand rather than in the fish stocks, while the whiting fluctuations may be due to the fact that this is largely a one-year-class fishery. In general, changes in landings of most species represent a balance between fishing effort and stock availability. It is difficult to achieve a direct single measure of total fishing effort since a number of different gears are used, but by converting to units of "100 hours fishing by seiners" an index of total fishing effort can be obtained which gives comparisons from year to year. This is included in Table I.

The highest landings of most species tend to be made in the months of January to April inclusive, when there is increased effort by small vessels in the comparatively sheltered waters of the Clyde. Hake are mostly landed only in midsummer.

In the pelagic fishery the mean annual landing over the past 10 years was 11,047 tons valued at £345.717. The three species involved are herring, sprat and mackerel, with herring very much dominant. Table 2 shows the landings since 1961 for the Clyde as a whole. A geographical division of the landings is more difficult for pelagic species, but nearly all the sprats and mackerel are taken from the upper Clyde, while the fishery for herring in the prespawning and spawning period in the spring is in the lower Clyde, and thereafter is almost exclusively in the upper Clyde. The spring spawning fishery on Ballantrae Bank and to the south of Arran is mainly with ring net and pair trawl although there is some fishing by tramel net. The main fishery, however, involves ring netters, although the increase in landings since 1969 can be attributed to the introduction of pair trawling on a significant scale. The absence of sprat landings from the Clyde in recent years does not necessarily indicate a population decline, but is a reflection of the technical problems involved in landing mixed catches of sprats and herring.

Finally, although this note is concerned with vertebrate fisheries, it should be noted that there are important shell fisheries within the Clyde sea area. Valuable catches of *Nephrops*, scallops and queens have been landed in recent years, and the longer established fisheries of lobsters, crabs, shrimps, winkles and mussels are still of considerable importance.

Table I Clyde Fisheries (Demersal) Landings in tons 1961–1970

		Cod	Haddock	Hake	Plaice	Saithe	Whiting	Total	Index
1961	Upper Clyde	90.7	102.6	68.3	40.3	7.7	115.5	483.6	770
	Lower Clyde	463.1	218.4	364.6	79.5	97.6	1473.9	2973.7	
1962	Upper Clyde	56.7	57.9	234.5	26.7	10.9	141.1	596.8	603
	Lower Clyde	402.7	157.4	796.3	71.4	79.4	1821.1	2668.4	
1963	Upper Clyde	57.9	48.2	160.6	11.4	10.3	145.6	502.1	366
	Lower Clyde	416.6	221.8	393.8	75.1	125.7	637.2	2237.6	
1964	Upper Clyde	98.4	111.6	48.7	17.1	18.2	295.8	634.1	506
	Lower Clyde	782.3	580.7	314.2	174.1	121.1	2272.4	4550.3	
1965	Upper Clyde	147.0	103.4	51.2	32.7	25.9	127.3	581.1	538
	Lower Clyde	1470.1	699.8	599.5	244.4	280.8	1544.7	5231.0	
1966	Upper Clyde	150.1	89.7	89.5	34.6	12.8	71.1	580.5	516
	Lower Clyde	1446.6	582.6	926.2	258.6	146.5	1819.7	5925.0	
1967	Upper Clyde	236.8	190.8	75.4	36.1	31.4	60.6	746.2	708
	Lower Clyde	1922.1	901.5	826.3	251.3	291.1	3096.2	7907.4	
1968	Upper Clyde	415.0	281.6	78.0	53.7	27.6	164.8	1239.1	640
	Lower Clyde	1857.8	614.6	705.4	210.1	233.0	1367.6	5866.3	
1969	Upper Clyde	382.6	170.3	68.1	43.9	50.9	69.7	953.6	520
	Lower Clyde	1842.4	617.3	577.5	161.3	503.8	1336.4	6367.9	
1970	Upper Clyde	353.8	124.2	108.4	43.4	188.6	30.2	987.1	335
	Lower Clyde	1452.3	573.1	554.9	118.9	1732.6	497.0	5413.9	

Hauling in the purseine net on a fishing vessel in the Clyde Estuary.

Table II Clyde Fisheries (Pelagic Landings in tons) 1961-70

	Herring	Sprats	Mackerel	Total		Herring	Sprats	Mackerel	Total
1961	12,214	76	907	13,197	1966	10,205	73	309	10,587
1962	3,521	1,969	181	5,672	1967	8,760	—	310	9,070
1963	7,009	1,013	240	8,263	1968	9,196	—	379	9,575
1964	14,898	180	256	15,336	1969	13,596	—	320	13,916
1965	15,392	687	208	16,287	1970	7,994	—	569	8,563

Sorting the catch on a scallop boat.

FISHERIES IN THE CLYDE

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A PHYSICS

1 Apparatus and methods
2 Hydrographic properties (salinity, temperature, density etc.)
  2.1 Salinity
  2.2 Temperature
3 Physical properties (diffusion, turbulence etc.)
4 Circulation and currents
  4.1 Circulation
  4.2 Currents
5 Freshwater flow
7 Tides and waves
  7.1 Tides
  7.2 Waves
8 Engineering works
9 Mathematical modelling
10 Pollution
11 Physical models
12 Miscellaneous

B CHEMISTRY

1 Apparatus and methods
2 Physical chemistry of sea water
3 Major elements
4 Trace elements
  4.1 Groups IA & IIA
  4.2 Groups IB & IIB
  4.3 Group III
  4.4 Group IV
  4.5 Group V
  4.6 Group VI
  4.7 Group VII
  4.8 Group VIII
    4.91 Rare earths
    4.92 Actinides
    4.93 Inert gases
5 Inorganics
6 Organics
  6.1 Oil
  6.2 Dissolved organic matter
7 Gases
  7.1 Oxygen
  7.2 Carbon dioxide
  7.3 Hydrogen sulphide
8 Biochemistry
9 Eutrophication
10 Pollution
  10.1 Pesticides
  10.2 Radioactivity
  10.3 PCB's
11 Nutrients
  11.1 Nitrogen
  11.2 Phosphorus
  11.3 Silicon
12 Miscellaneous

C GEOLOGY

1 Apparatus and methods
2 Bathymetry and topography
3 Solid geology
4 Sedimentation
  4.1 Suspended particulate material
5 Sediments
6 Geochemistry
7 Palaeontology
9 Salt marshes
10 Pollution
12 Miscellaneous

D BIOLOGY

1 Apparatus and methods
2 Plankton
  2.1 Phytoplankton
  2.2 Primary production
  2.3 Zooplankton
  2.4 Secondary production.
3 Nekton
  3.1 Commercial fish
  3.2 Non-commercial fish
4 Macroalgae
5 Benthos
  5.1 Commercial benthos
    5.11 Oysters
    5.12 Cockles
    5.13 Mussels
    5.14 Decapods
    5.15 Scallops
    5.16 Fish
  5.2 Non-commercial benthos
    5.21 Sponges and coelentrates
    5.22 Platyhelminthes
    5.23 Nematodes
    5.24 Polyzoa
    5.25 Molluscs
    5.26 Annelids
    5.27 Crustacea
    5.28 Echinoderms and ascidians
    5.29 Fish
6 Microbiology
  6.1 Bacteria
    6.11 Sewage bacteria
    6.12 Non-sewage bacteria
  6.2 Bacterial production
  6.3 Bacterial destruction
  6.4 Yeasts
7 Birds
8 Biochemistry
9 Salt marshes
10 Pollution
11 Ecology
12 Miscellaneous

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PARTICIPANTS AT MEETINGS OF THE CLYDE STUDY GROUP

At a meeting arranged in the University of Glasgow on 9 June 1971 it was decided to undertake a review and appraisal of the knowledge which existed about the Geological, Physical, Chemical and Biological features of the Firth of Clyde. First drafts of papers on these subjects were considered at a meeting held in the University of Strathclyde on 28 October 1971. Following this some additional material was prepared. All the material has now been brought together and a short synopsis included.

The people who have participated in the meetings are listed below:

Prof. N. Millott	Universities Marine Biological Station, Millport. *Chairman.*
Dr. G. Topping Dr. J. H. Steele	Department of Agriculture & Fisheries for Scotland, Aberdeen.
Prof. D. R. Newth Prof. J. D. Robertson Dr. A. D. Boney Dr. T. A. Norton	University of Glasgow.
Mr. R. I. Currie Dr. P. R. O. Barnett	Scottish Marine Biological Association
Prof. E. O. Morris Dr. E. J. Perkins	University of Strathclyde
Mr. J. I. Waddington Mr. D. Hammerton Mr. D. W. McKay	Clyde River Purification Board
Mr. R. S. Glover	Institute for Marine Environmental Research
Dr. G. W. Heath	Secretary of the Study Group

The above attended the first and second meetings and those shown at right attended the second meeting:

Dr. A. D. McIntyre	Department of Agriculture & Fisheries for Scotland, Aberdeen.
Dr. A. V. Holden	Department of Agriculture & Fisheries for Scotland, Pitlochry.
Mr. J. Gilligan	Clyde River Purification Board
Dr. J. R. Rossiter	Institute of Coastal Oceanography & Tides*
Dr. L. Carter	Imperial Chemical Industries
Dr. C. E. Deegan	Institute of Geological Sciences, Edinburgh
Prof. D. I. H. Barr Dr. P. H. Milne Mr. R. H. F. Collar and colleagues	Department of Civil Engineering, University of Strathclyde
Dr. J. C. Smyth and colleagues	Paisley College of Technology
Mr. P. Barnes	Ayrshire River Purification Board
Dr. J. Bogan	Veterinary Pharmacology, Glasgow University
Dr. P. G. Moore	Universities Marine Biological Station, Millport
Prof. A. C. Wardlaw	University of Glasgow, Microbiology Department
Prof. J. S. Webb and colleagues	Imperial College of Science & Technology, London

In addition four observers from other Estuarine Study Groups attended the second meeting:

Dr. A. P. M. Lockwood vice Prof. J. E. G. Raymont – Southampton University.

Dr. T. L. Shaw vice Prof. D. L. Dineley – Bristol University (Sabrina Project).

Dr. D. F. Shaw – Liverpool Bay Study Group.

Dr. L. J. Hale – Forth & Tay Study Group.

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